Designing Airport Passenger Buildings for the 21st century : Matching Configuration and Internal Transport Systems

by

Chai-Teck Phua

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Signature of Author ....
Department of Aeronautics and Astronautics

Certified by ....
Professor Richard de Neufville
Chairman, Technology and Policy Program
Thesis Supervisor

Accepted by ....
Professor Peter P. Belobaba
Chair, Transportation Education Committee

Accepted by ....
Professor Harold Y. Wachman
Chairman, Department Graduate Committee

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Abstract

This thesis attempts to identify optimal combinations of airport passenger buildings and internal transport technologies for passengers and bags. The analysis is based upon extensive data about passenger/baggage transport systems obtained through reports and field visits.

A universally applicable computerized spreadsheet model is developed to determine the multiple criteria performance of all possible combinations of technology and building configurations over a range of situations. It uses queuing theory. Decision analysis is adopted to select the "best" combination over time.

Specifically, the study focused on four possible future midfield and hybrid passenger building configurations: Midfield Linear, Midfield "+", Hybrid Centralized Linear with Midfield Linear, Hybrid Centralized Pier with Midfield "X". Three passenger transport technologies are analyzed : self-propelled and cable-driven automated people movers (APM), conventional shuttle buses and moving sidewalks. Three baggage transport systems are compared : multi-bag cart (telecar), single-bag destination-coded vehicle (DCV), and non-automated tug/carts.

The cable-driven APM (for passengers) and the tug/cart (for bags) combine best with the Hybrid Centralized Linear with Midfield Linear configuration for a smaller 28-gate airport. The same building configuration provides good performance with the self-propelled APM and DCV system for a larger 56-gate airport. The latter combination also appears to be the most robust over the longer term range of situations.

Finally, we demonstrate the applications of our findings to some existing and future international airports.

Thesis Supervisor : Richard de Neufville
Title : Professor and Chairman, Technology and Policy Program

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CHAPTER 1 - INTRODUCTION

1.1 Motivation

Errors in the selection of a particular technology for moving passengers or bags in the initial stages of design of an airport passenger building can be extremely costly. The prevention of design errors for an airport terminal can amount to millions of dollars in savings. It is believed that the avoidable design errors for the new "controversial" automated baggage handling system at the new Denver International Airport resulted in at least an additional US$50million in expenses to put in a manual back-up system at the last moment. This is in addition to the extra costs of about $1million a day over a period of sixteen months for not having the airport opened on time. This example is surely not an isolated incident. The design of a certain technology for a particular airport passenger building configuration may appear sound at the inception, yet, over time, may become inappropriate for future environments. Therefore, it is critical to consider in the overall design strategy how a particular technology and configuration will perform under conditions of change.

Prevalent in the current practice of selecting a technology and/or a configuration of passenger buildings is the notion that performance can be addressed by considering only a single forecast and that performance can be described using only a limited number of measures. This philosophy neglects the near certainty that the airport will almost certainly witness major changes in traffic patterns over the course of its useful life. Therefore, significant operational difficulties will be encountered if the potential for change is ignored.

1.2 Performance Measures

In assessing the potential performance of a particular technology and configuration, comparisons are often made using a single measure of performance, such as, passenger walk distance, and again a single statistic to describe that measure, i.e. maximum or average walk distance. Perhaps the more important shortcoming in the comparisons made using a single measure of performance is that of a single set of conditions, for example, loads, rather than for a number of different scenarios. Good design practice dictates the need to perform over a range of different conditions as opposed to simply the expected one.

Robustness, or the ability to exhibit consistent performance over a variety of uncertain conditions is generally better than exceptionally good performance in some cases and poor performance under others. The inability to predict future conditions accurately makes the selection of a robust system critical to the long term success of an airport. Hence the selection of an initial technology for a certain configuration should be a strategic decision, one that considers the ability of the chosen system to cope with major changes in the uncertain aviation environment. This is far better than relying on the decisions of airport operators to adapt an undesirable system (often at great expense) each time conditions change.

Performance should be thought of as a function of many measures instead of just one. Rather than trying to achieve the best system based on a single forecast and measured by a single measure of performance, the design strategy should consider multi-performance measures encompassing a variety of possible futures in the selection process. As mentioned above, aviation forecasting is an inexact science, due to the massive uncertainty associated with the factors used to predict future aviation demand [de Neufville, 1976]. Examples include various economic indicators, predictions about future patterns of airline service and technological advances in Air Traffic Control and aircraft types.

From a passenger's perspective, the performance of an airport depends on walk distances, minimal wait times, overall travel times, and never have to miss a flight. From the airport operator and airline's perspective, performance with respect to passenger and bags can be assessed by various measures such as the extent of queues and delays to passengers / bags, overall travel / delivery times and the cost of the system. These all depend on the type of technology provided and on the kind of configuration adopted for the airport.

The role of an airport designer is to try to achieve a balance in the performance of the different measures in the selection of an initial technology and configuration. Such a balance is best achieved when performance is considered in a multi-dimensional context over a broad range of situations. The following measures will be considered in the analysis of the performance of the different technologies and the corresponding airport passenger building configuration:

a) Average and maximum length of queues;

b) Average and maximum door-to-door travel times, which includes the walk times, wait time in queue, transit time, loading/unloading times, vehicle maneuvering time, where appropriate, and sortation / baggage conveyance time;

c) Average and maximum walk distance for passengers;

d) Cost of the system.

1.3 **Computer Model**

To estimate the above performance measures, a flexible computer-based spreadsheet model has been developed. This model enables one to carry out an analysis of the multi-criteria performance of any given combination of technology and airport passenger building configuration over a range of loading conditions. It allows the design team to ask "what-if" questions readily, and is based primarily on the theory of queues.

Chapter 5 provides details of the model and the assumptions adopted together with sample numerical calculations.

1.4 Review of related studies

Traditionally, part of the airport planning process consists of the development of the terminal layout plan which includes decisions regarding the configuration of the passenger buildings. This is essentially a two-stage process, beginning with the initial selection of a configuration concept and proceeding with the development of a detailed floor plan.

There is little evidence of any consideration being given to the integration and performance of the major internal transport systems, namely the people mover and baggage systems, at the initial planning level. Such decisions are usually made after the selection of the passenger building configuration and the transport systems are then made to "fit" into the selected concept often with great difficulties.

The initial planning effort does not take into account the selection of the best combination of technology and configuration that will perform well over the longer term. For good planning purposes, there is a need to consider the performance of the different technologies jointly with the selection of configuration early in the planning process. This will lead to an optimal decision that will guarantee good performance over the long term, with the flexibility to respond to changing conditions.

Currently in the selection of an initial configuration, two forms of decision supports exist, namely, reference manuals and texts, and analytic techniques [Svrcek 1994]. Reference manuals and texts provide very broad information and standards developed by regulatory groups such as FAA, IATA and ICAO. They contain general discussions of the key advantages and disadvantages of different configurations on a superficial basis with little or no quantitative evidence to support their statements. Moreover, the descriptions are generally based on a single, often unspecified set of conditions, with no mention on how the advantages and disadvantages would differ under changing conditions.

Analytic techniques define potential configuration performance in terms of quantitative measures such as passenger walk distances. However, such methods impose several unrealistic simplifying assumptions about the operations and use of passenger terminal buildings. For example, a common assumption is that of uniform gate size, aircraft utilization, and distribution of passengers within each concourse [Bandara, Robuste, Vandebona, Wirasinghe]. Such a uniformity assumption, although making the equations simple to represent, does not take into account what truly occurs in practice, whereby certain gates are favored for different aircraft based on issues such as maneuverability and passenger convenience. Hence the average number of seats arriving and departing from each gate is not constant. Moreover, such analytical techniques provide little information as to how the configurations would perform over a range of loads. Wirasinghe and Bandara [1992] examined the planning of midfield parallel pier airport passenger buildings such as Atlanta's Hartsfield and the new Denver Airport, which employ automated people mover(APM) systems for transport between piers. They found that the geometry which minimized total system disutility (of walking, using APM, cost of APM) consisted of a non-uniform set of piers with longer piers towards the terminal block.

The second step in the development of terminal layout plan is the creation of detailed floor plans where decisions such as the general space requirements for various terminal facilities are made. Again, reference manuals and texts provide the basic guidelines, through a series of charts and figures. These however, do not capture the dynamic nature of passenger flows throughout the building. As a result, a series of computer-based simulation programs have been implemented to aid airport planners. Detailed Monte-Carlo simulation programs exist which attempt to represent the dynamic nature of the airport environment. These programs require flight schedules and detailed information regarding the passenger building configuration. But acquiring such input data can be extremely time consuming, not to mention the setup time involved and the computation time. These analysis enables one to obtain estimates of passenger building configuration performance in terms of queues, waiting times, walk distances, etc. However, the total cost in terms of time expended makes such analysis unattractive.

Studies so far in the area of people movers have focused on the analysis of the impact of automated people movers on various airport configurations in terms of only a single or at most two performance measures, usually the maximum walk distance and/or average travel time [Shen 1989,1990, 1992]. There is little evidence of any broad-range comparison made over several performance measures. Moreover, it is doubtful whether the effects of queues under the different loads have been accounted for in Shen's analysis of travel times. Sproule [1989, 1991] states that APMs are attractive because of their operational flexibility, reliability, cost-effectiveness, safety, reduces walk distances etc. Other than giving a general overview of their current airport applications, inadequate analysis has been carried out to suggest that the APM systems, according to Sproule, "have proven themselves and are a success". More importantly, there appears to be very little work comparing the performance between different automated people mover technologies i.e. self-propelled Vs cable-driven systems, with the non-automated alternatives, such as shuttle buses and moving sidewalks, for the different airport passenger building configurations. Evaluation of baggage transport systems have received even far lesser attention.

It appears that currently, only "rule-of-thumb" techniques or previous experiences have governed the decision on the need for automation. There does not exist a methodological way of evaluating the range of alternatives available over a broad range of measures and loading conditions, and also on making the best decision over the longer term.

The intent of this thesis is to fill this gap by developing a methodology and a flexible computer-based tool that will allow us to establish the multi-criteria performance of any combination of technology and passenger building configuration over a broad range of situations, with the intention to ultimately select the best "match" for the longer term. With this, we are now able to address an issue in airport planning that was previously unaddressable.

1.5 Problem Definition and Structure of Thesis

This thesis : (1) develops a methodology to help airport planners establish the performance of any combination of technology (people mover / baggage transport) and passenger building configuration in a broad range, multiple criteria context, and (2) applies it to the selection of both the best technology for a given configuration, and the best combination of technology and configuration over a future that is highly uncertain.

Chapter 2 discusses the major passenger building configurations. These can be placed into just a few standard categories based on their primary geometry and functional characteristics. Chapter 3 presents a detailed discussion of the current technology for transporting passengers and baggage based upon an information database that is developed as part of the thesis.

Chapter 4 presents the assumptions and the approach upon which the analysis is based. Geometric representations of the building configurations introduced in Chapter 2 is developed so as to provide a consistent platform for comparing and contrasting the different configuration concepts objectively. These geometric representations are used to obtain the absolute distances between points within a given configuration, which are inputs to the queuing model developed in Chapter 5. Taking into consideration preferential gate assignments, we present our assessment of the overall estimated walk distances for the various concepts as well as the comparison of areas required for the different passenger building configurations.

Chapter 5 reviews queuing theory, which is used as a basis for developing the computer model. It discusses the algorithm as well as the principle outputs of the model. It also presents a numerical example for a sample combination of technology and configuration to demonstrate the techniques introduced throughout the chapter. Chapter 6 describes the methodology and the decision analysis tool used for establishing the overall best combination of technology and configuration over time given the highly uncertain probabilistic future, in the form of decision trees.

Chapter 7 uses the model developed in Chapter 5 to assess the potential performance of all combinations of technology and configuration over various criteria measures for a range of possible loading conditions. The analysis for passengers and baggage are treated separately. Results are presented in the form of various "performance profiles" over various situations for a given configuration. These establish the most robust technology for a given configuration, and determine the best combination of technology and configuration, for each of the two airport sizes. Using the Decision Analysis tool described in Chapter 6, it is possible to decide systematically on the best combination over the time dimension for various probabilities of future growth. Finally, Chapter 8 presents the conclusions and discusses general applications to some existing/future airports.

CHAPTER 2 - AIRPORT PASSENGER BUILDING CONFIGURATIONS

Many different configurations exist for airport passenger buildings. Yet virtually all can be placed into a few primary categories based on their geometrical characteristics and functional philosophy. Furthermore, each of these can be divided into centralized and decentralized sub-categories depending on the operational philosophy for processing passengers.

In general, centralized configurations are characterized by a single common passenger processing area containing check-in, baggage handling and other facilities for all airlines. Decentralized configurations, sometimes known as "unit terminal" concepts, have passenger processing facilities for airlines located in separate buildings. These duplicate manpower and equipment in all buildings and could be more costly to manage, operate and control than the centralized configurations. Although generally reducing the walk distances of originating and terminating passengers, decentralized configurations can increase walk distances for transfer passengers whose departure gate is not located within the same arrival concourse [de Neufville and Rusconi-Clerici 1978].

2.1 Centralized Gate Arrival / Linear configuration

The first airport passenger buildings were designed to provide a direct interface between airport access modes and aircraft which dock directly against the building. Known as the gate arrival or linear design, all necessary passenger facilities e.g. check-in, baggage are contained in a single building. More importantly, it allows for short walk distances between curbside and departure areas and is therefore suited for shuttle services where the bulk of the passenger traffic tends to be business travelers who generally do not carry much baggage and tend to arrive at an airport close to departure time. Examples of centralized linear configuration are the recently opened new International Terminal 5 at Chicago/O'Hare (see Figure 2.1) and the USAir Terminal at New York/LaGuardia.

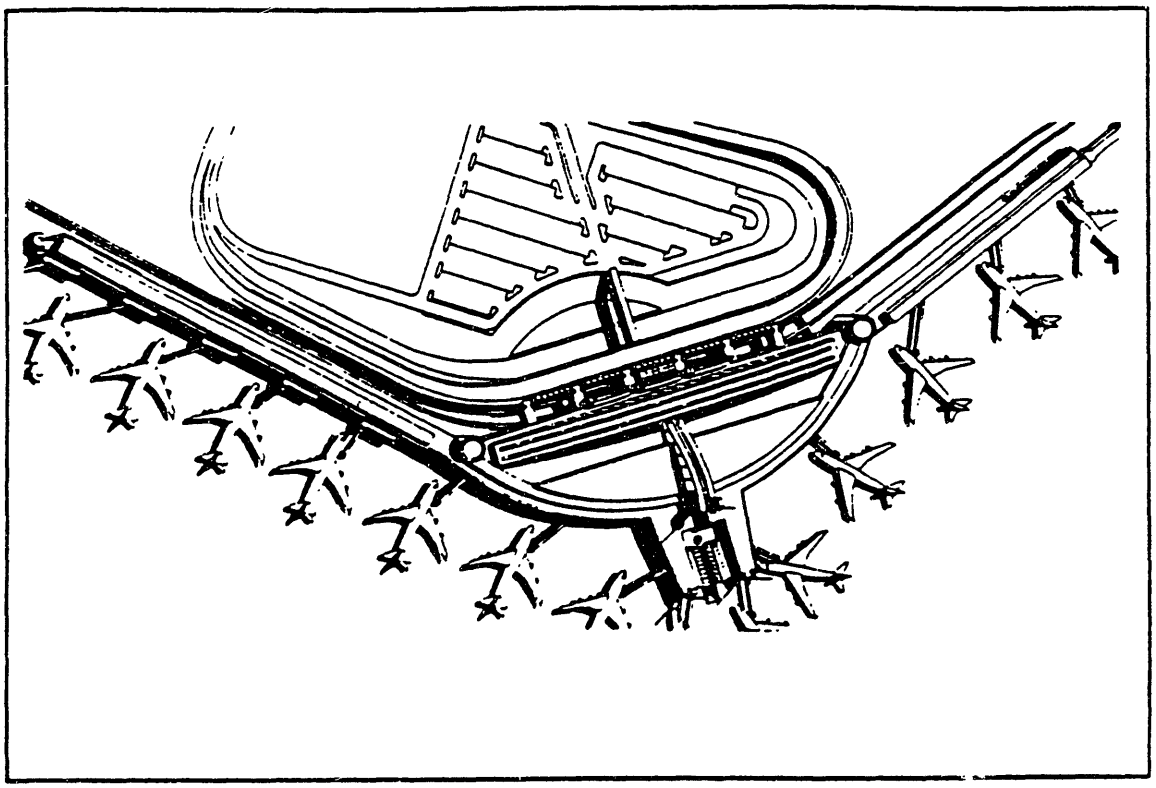


Figure 2.1 : Terminal 5 at Chicago/O'Hare International Airport

2.2 Centralized Pier configuration

Increases in the volume of passenger traffic and the resulting need for more aircraft stands brought about the second generation of passenger building configurations, which included the introduction of piers. Piers could be attached to the existing linear terminals and therefore increase the number of gates available at an airport due to the additional airside frontage for aircraft which tend to dock on both sides. Walk distances for originating and terminating passengers increased as aircraft gates had to be reached through a series of corridors. Rather than having one common passenger holding facility, airlines moved towards having separate holding facilities for each flight. Passengers could then be processed and held in lounges directly adjacent to aircraft. Figure 2.2 illustrates the centralized pier configuration at Terminal 1 of Frankfurt Main Airport.

2.3 Centralized Satellite Configuration

When further increases in traffic volumes could no longer be handled by adding piers to existing passenger buildings, a third generation of configuration for airport passenger buildings, known as the satellite concept evolved.

The major difference was that departure concourses were now completely separated from the original passenger building, and access to them was achieved via above- or below-grade connectors, transporter buses, or other forms of mechanical devices such as moving sidewalks and automated people movers, given the increased distances between a passenger's access point and the aircraft interface. This concept was originally intended to improve aircraft maneuverability by separating aircraft stands from the landside passenger building, thus potentially reducing apron congestion. To further facilitate maneuverability, many satellite concepts are constructed with below-grade connectors (from the landside building to the satellites), allowing aircraft to be parked around the entire satellite perimeter to gain maximum frontage and without

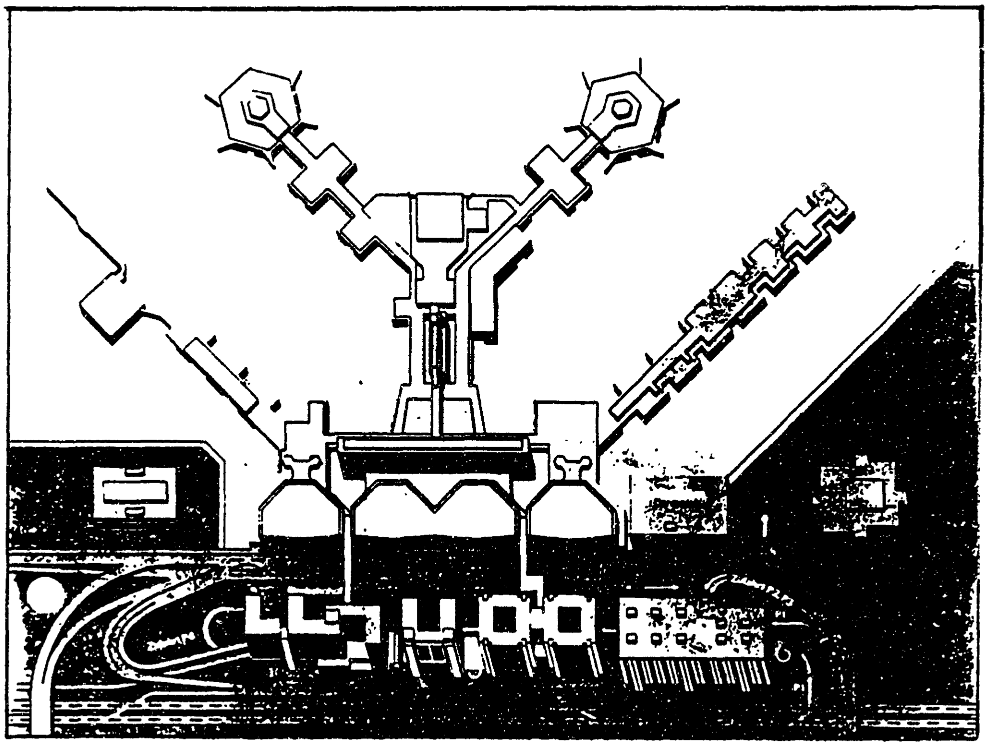


Figure 2.2 : Terminal 1 at Frankfurt Main Airport

creating cul-de-sacs during entry and exit. The landside passenger building houses most of the passenger processing facilities, though some may be located within the satellite. Satellite concourses can take many different shapes, including circles, rectangles, T and Y shapes, as well as various hybrid combinations.

An example of a satellite concept is Building 1 at Paris/Charles de Gaulle Airport where seven satellites are arranged in a radial fashion and connected underground via moving sidewalks to a common central landside passenger building (see Figure 2.3).

2.4 Midfield Configuration

The most recent evolution of configuration concepts is known as the midfield design. Like the third generation satellite concept, individual passenger building concourses are disjoint from the main landside building, and access to departure gates typically involve some form of people moving device to avoid excessive long walking distances. Concourses can be arranged in a variety of patterns, depending on geographical limitations and operational philosophy. These are situated out in the midfield between parallel Runway systems. Figure 2.4 shows the layout of the new Denver International Airport where the midfield concourses are arranged in a linear fashion parallel to one another.

Originating passengers enter a landside building and go through passenger processing, before boarding an underground automated people mover system that takes them to the center of their respective departure concourse. Transfer passengers either use the train to get between midfield concourses or remain within the same concourse for their connections. Because the train is below-grade, aircraft can be parked on all sides of the rectangular concourses and taxiways do not end in cul-de-sacs. In fact, dual-taxiways are provided between all concourses for more efficient aircraft movement.

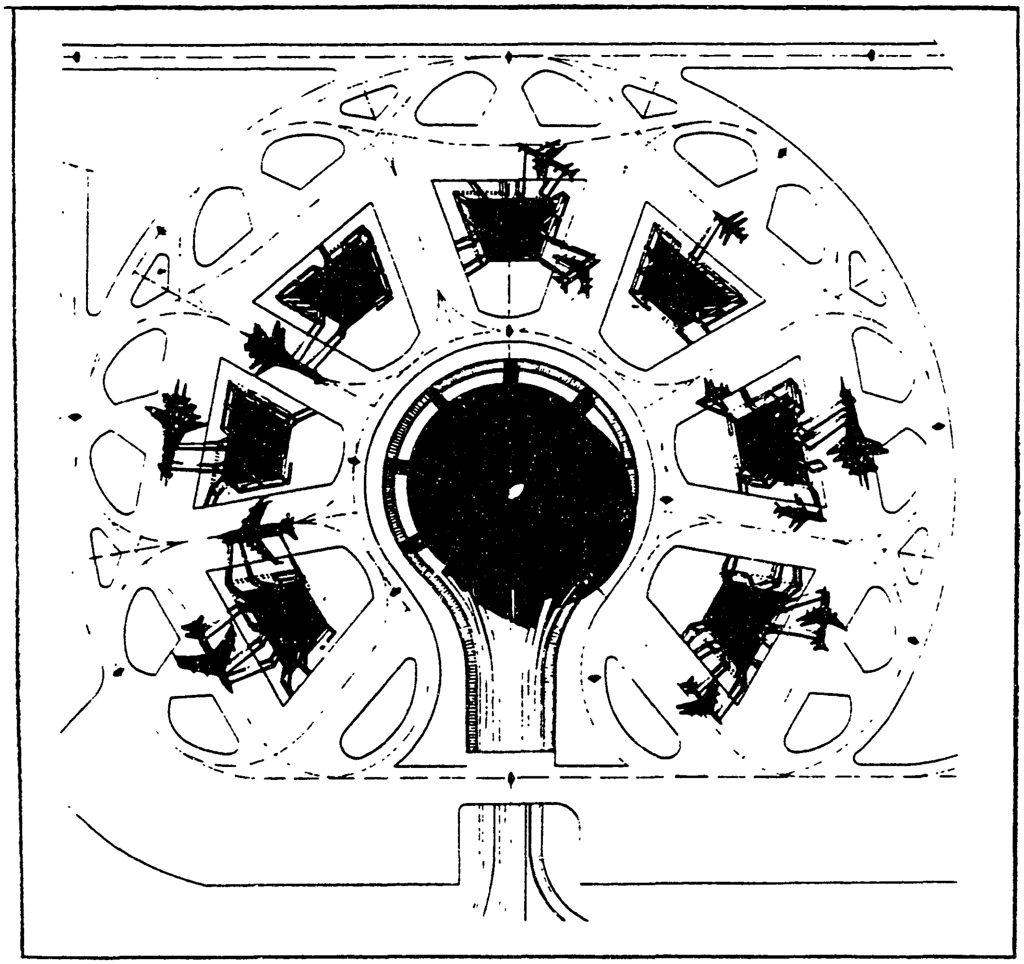


Figure 2.3 : Building 1 at Paris/Charles de Gaulle Airport

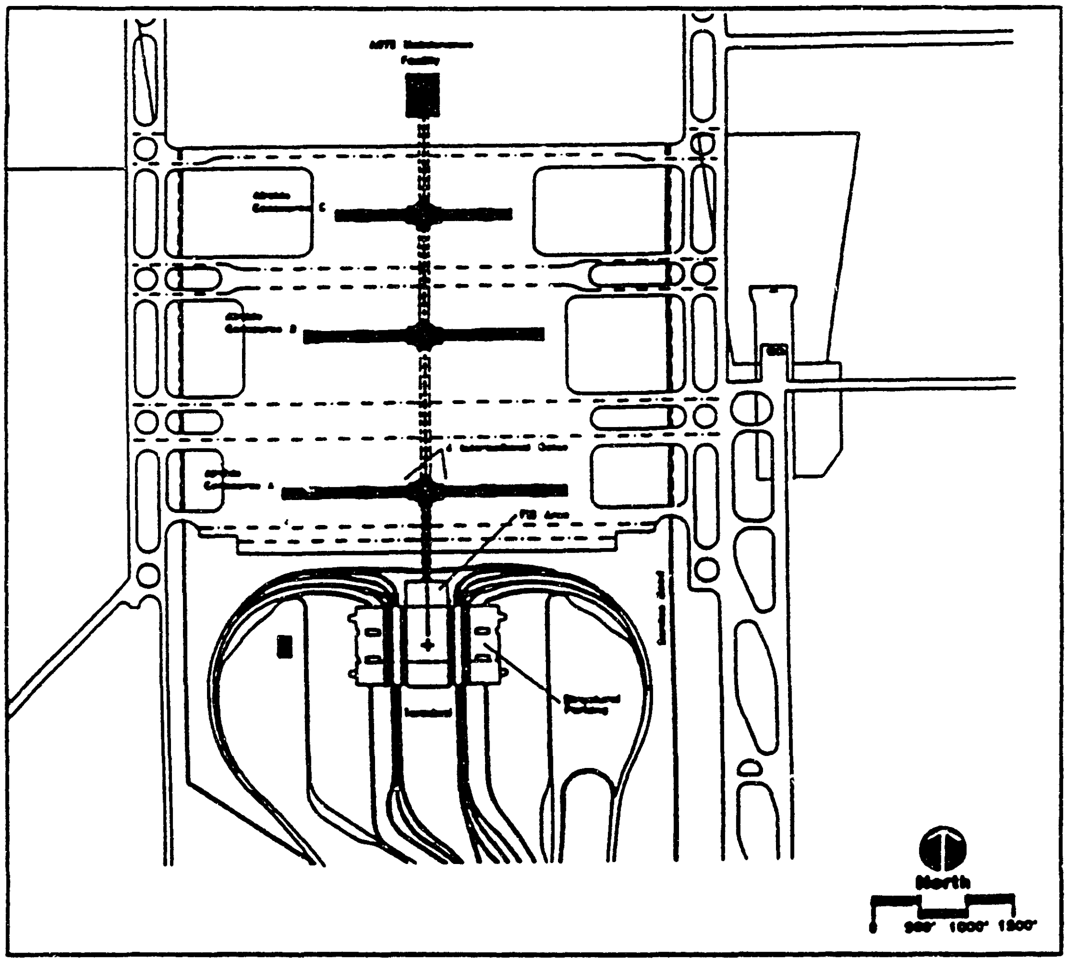


Figure 2.4 : New Denver International Airport

Given the advantages of midfield configurations for connecting passengers, they are becoming an increasingly popular concept for airports expecting a high level of transfer traffic [de Neufville 1994].

2.5 **Hybrid Configuration**

Most airports configurations are in fact a mixture of operating philosophies. So called "hybrid" configurations take on the characteristics and attributes of two or more of the standard configuration concepts. An example of this is the Atlanta Hartsfield International Airport which is a hybrid combination of a centralized linear with midfield linear design, almost similar in layout to that of the new Denver International Airport but with some gates directly adjacent to the landside building. It can thus operate like a gate arrival or linear concept (see Figure 2.5).

Two other examples of hybrid configurations are the new Pittsburgh International Airport and Hong Kong/Chek Lap Kok Airports (see Figure 2.6). Both are similar in that they are a hybrid combination of a centralized pier with a single midfield "X"-shaped concourse. Other airports, such as the new Kuala Lumpur International and the Second Bangkok International Airports will each have at least two similar midfield "+"- shaped concourses.

Hong Kong/Chek Lap Kok will have a "Y"-shaped finger pier connected directly to its centralized passenger processing facility, and can thus also operate like a gate arrival or linear concept. For short-haul originating and terminating passengers, the gate arrival concept minimizes walk distance by providing direct interface between ground access and aircraft. For long-haul connecting passengers who do not require intermediate services, the "X"-shaped concourse provides convenient access between their arrival and

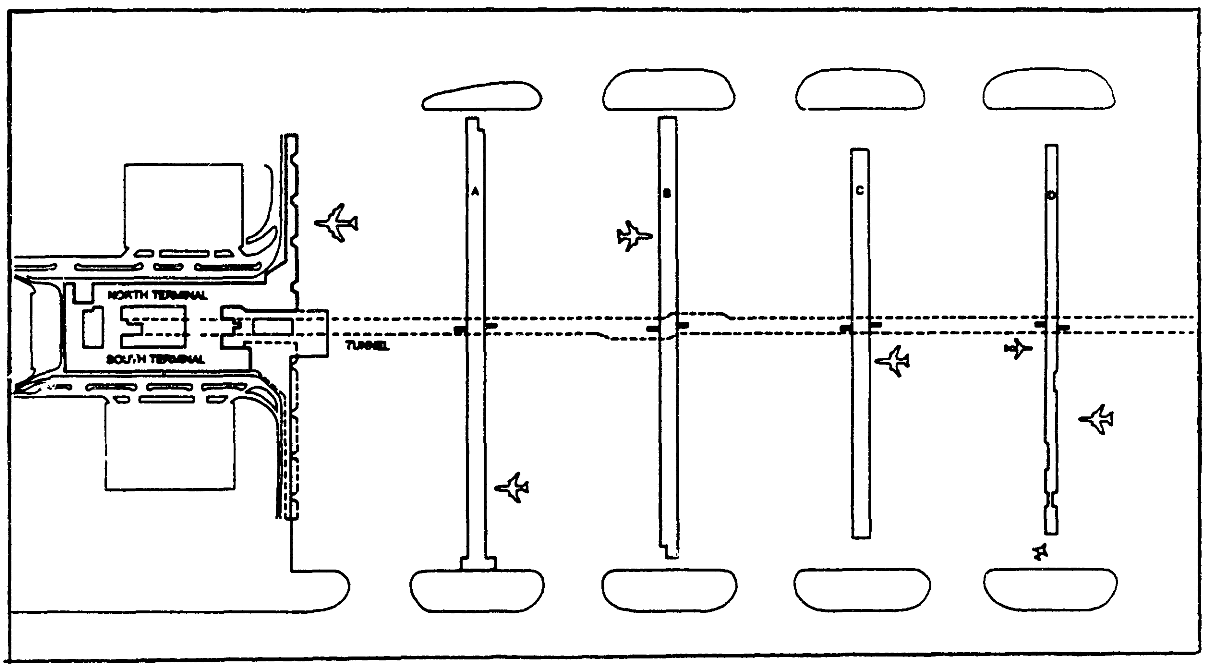


Figure 2.5 : Atlanta Hartsfield International Airport

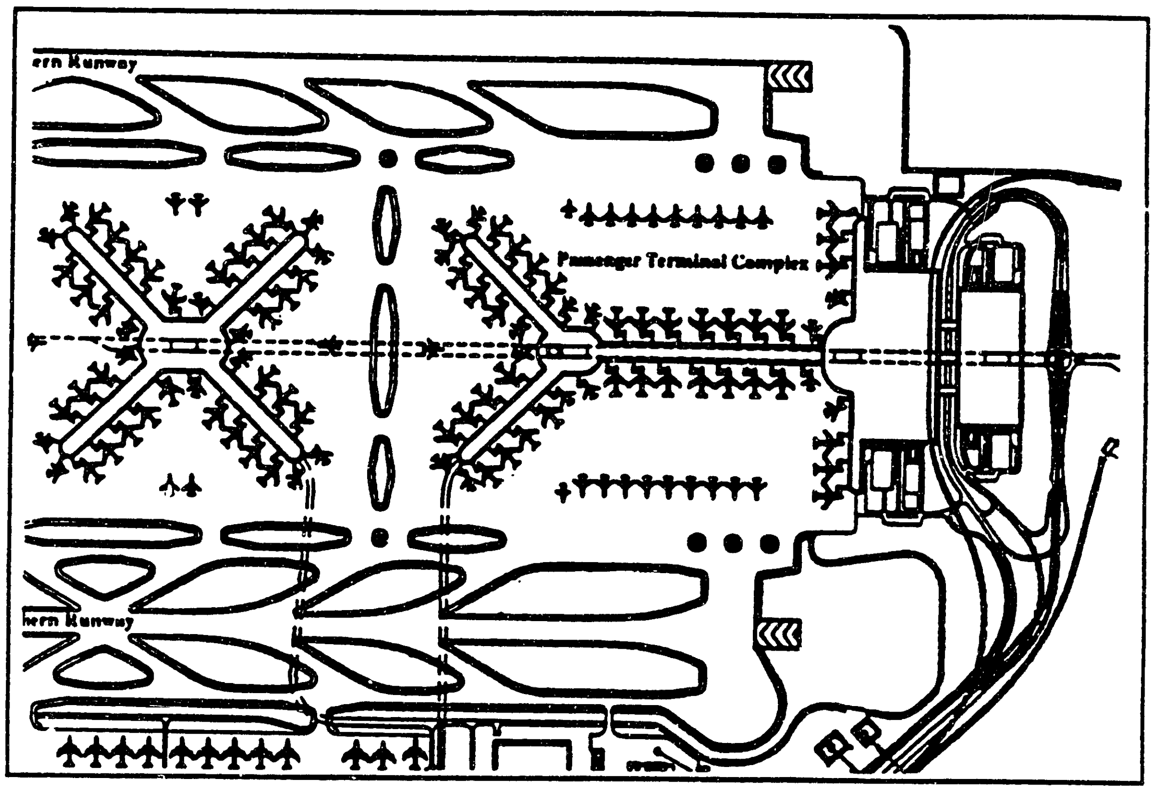


Figure 2.6 : Proposed Hong Kong /Chek Lap Kok Airport

departure gates without the need to leave the midfield environment. However, long-haul originating and terminating passengers will in general, experience longer distances between curbside and their aircraft. But as these passengers tend to arrive earlier than domestic (short-haul) passengers at the airport, they will have more time to reach their gates.

The Hong Kong/Chek Lap Kok example illustrates an important advantage of hybrid configurations, namely, the combination of the most desirable features from two or more standard configuration types in an attempt to match the anticipated passenger traffic. By utilizing both a gate arrival and a midfield concept, the airport is potentially able to provide a better level of service to both passenger types, rather than sacrificing service of one for another. Hence the combination of concepts is likely to outperform any single standard configuration given the passenger traffic anticipated.

In the long run, the hybrid concept is likely to provide even further advantages. Because of its flexible design, major changes in passenger traffic can be accommodated without severely degrading performance [de Neufville 1976]. If Hong Kong continues to be an increasingly popular transfer point, another "X"-shaped midfield concourse can be constructed to handle higher passenger transfer loads. But if there is an increase in originating and terminating traffic, then the linear frontage can be extended to provide more aircraft stands.

Chapter 4.1 presents some of the latest airport passenger building configurations discussed above, namely, the midfield and hybrid configurations, geometrically so as to provide a means of comparing and contrasting the concepts objectively. These configurations may well represent the design of many airport passenger buildings in the 21st century, and are therefore the focus of this thesis in an effort to determine the most optimal combination of technology and configuration.

CHAPTER 3 - CURRENT TECHNOLOGICAL SYSTEMS

This chapter reviews the different technologies in use around airports today for transporting passengers and baggage. It describes the following people mover devices:

a) Automated People Movers (APM) - self-propelled, cable-driven

b) Shuttle Buses

c) Moving Sidewalks

It then discusses the following three systems for the transportation of bags from the landside building to aircraft / concourse and vice versa:

a) Automated multi-bag cart system (known as the telecar)

b) Automated single-bag destination coded vehicle (DCV)

c) Tug and Cart

There is a significant difference in the handling of passengers and baggage. Bags involve added manual interaction requiring time to load/offload and sort (manually or automatically). Unlike bags, passengers "sort" themselves out automatically by finding their way to their respective gates. They are usually more sensitive to the speed of travel from point-to-point, and generally require minimal assistance in eventually reaching their destination (i.e. gate).

3.1 **Database Information System**

A database containing the latest available information to-date on the various automated people mover and baggage handling systems at major airports around the world has been developed. It includes many fields, such as the country of origin, airport, type of technology available, number of systems in place, system configuration, distance covered, year of operation, demand, capacity, system cost (both capital and operating / maintenance), and cost on a per passenger/bag basis.

This chapter draws upon the database as a primary source of information to present the current state of technology. The other advantages of creating a database are that information can be easily extracted and presented in whichever format one desires for reporting purposes, as demonstrated in this chapter, and updated from time to time.

3.2 People Mover Technologies

A consequence of the massive growth in air travel is that the scale of modern passenger buildings often exceeds human proportions. In order to achieve designs with acceptable passenger walk distances and travel times, more reliance is being placed on transport technology. General increases in air transport activity and the development of hubs will continue to make the problem of passenger mobility a more important part of airport planning and design to overcome the increasing distances associated with late 20th century airport passenger buildings. Although much emphasis is placed currently on connecting passengers, there are very large numbers of origination / destination passengers who want to go to or from hub cities. These passengers too must confront the great distances and times associated with hub airports.

3.2.1 Automated People Mover (APM)

The Automated People Mover (APM), sometimes referred to as Automated Guideway Transit (AGT), is a class of transit characterized by :

a) Automatic (driverless) control

b) Discrete vehicles with nominal capacities of up to 100 passengers operating on an exclusive right-of-way (batch system)

c) Use of a guideway to control the path of the vehicles

d) Maximum speeds of 8 to 50 mph

e) System capacities ranging from 1000 to 14000 passengers per hour per direction (pphpd)

APMs are proprietary systems with many technological features such as propulsion, suspension, and control subsystems varying considerably between suppliers. Four types of APM configurations are usually considered for airport applications. These are depicted in Figure 3.1 and described below:

Fig 3.1 shows linear alignments only. However, APMs can operate successfully over horizontal curves at a minimum radius of 30 to 60 m (Leder 1991).

Single-Lane Shuttle : One train moves back and forth on a single guideway lane. The trains reverses direction at each end-of-line station.

Dual-Lane Shuttle : There are two independent guideway lanes. One train on each lane moves back and forth, reversing direction at each end-of-line station. To provide the highest level of service, the train movements are synchronized.

By-Pass Shuttle : There is a single guideway lane with a short dual section to allow trains to pass each other. Two trains move back and forth, reversing direction as explained above.

Pinched-Loop : There are two parallel guideway lanes connected at each end by crossovers, forming a "collapsed" loop. Trains cross from one guideway lane to the other and reverse direction. The loop configuration permits more than two trains to operate at any time with headways as low as 90 seconds. The pinched loop also has the flexibility to be operated as a single or dual lane shuttle, during off-peak or maintenance periods.

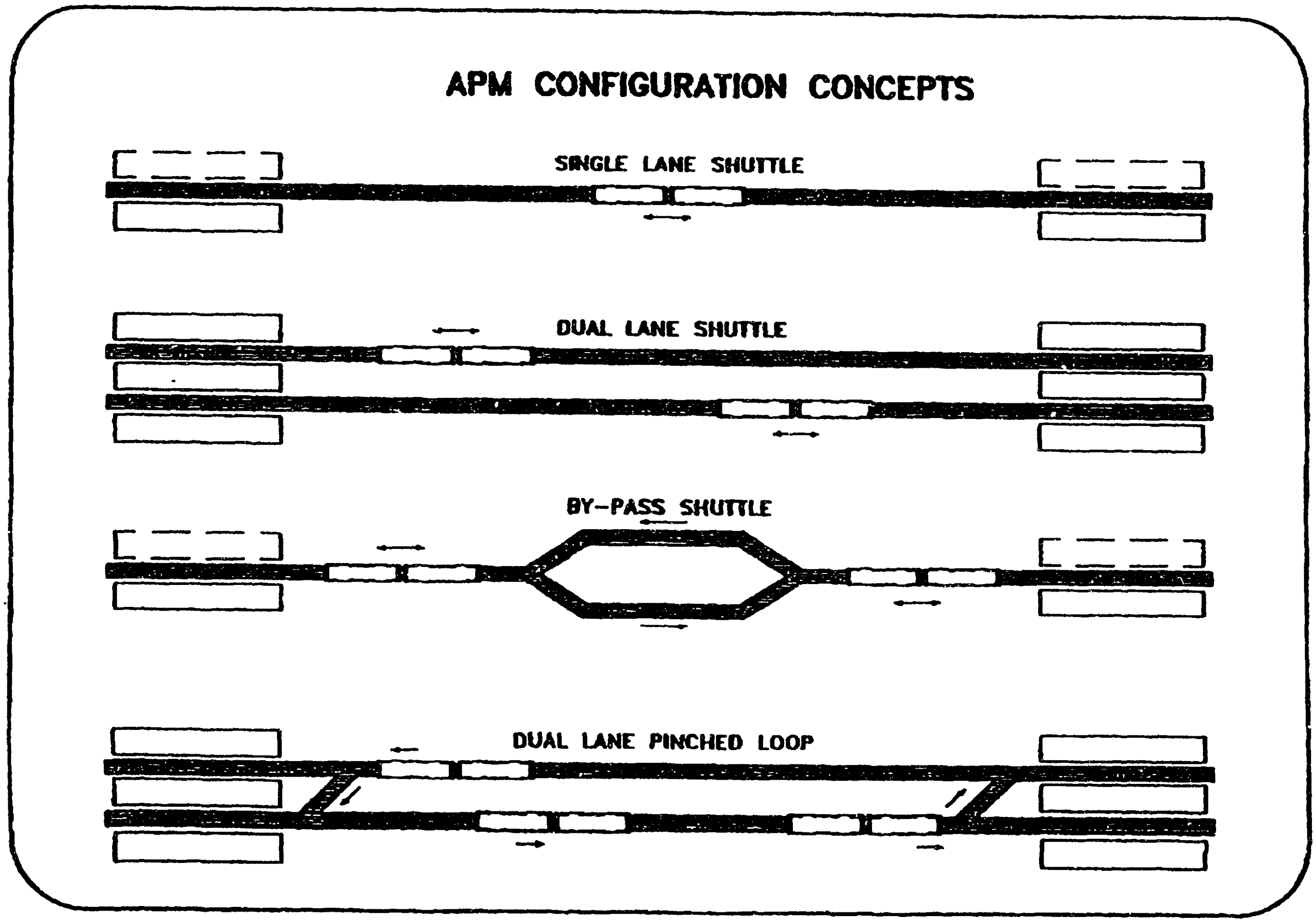


Figure 3.1 : Automated People Mover Configuration Concepts

Dual-Lane shuttles (e.g. Cincinnati, Pittsburgh, London/Gatwick) and Pinched-Loop configurations (e.g. Chicago/O'Hare, new Denver, Frankfurt) are by far the most common at airports today. See Table 3.1 which lists the more recent automated airport people mover systems over the last 7 years. Both dual-lane shuttles and pinched-loop configurations offer frequent service, high capacity and inherent reliability (due to the redundancy of having two lanes), as compared to single-lane (e.g. Singapore/Changi) or by-pass (e.g. Tokyo/Narita) shuttle configurations. Point-to-point distances for the dual-lane shuttles vary between 300m and 1.2km (see Table 3.2). For longer distances requiring multiple stops and high capacity , the pinched loop system is adopted. Such distances range between 1.1 to 4.4 km (see Table 3.3).

Pinched-Loop systems are generally more expensive and complicated due to the more sophisticated train control architecture where additional collision controls and switching/failure mechanisms are required. A by-pass shuttle is expected to provide less availability than the dual-lane and pinched-loop configurations since most of the guideway is shared and stations are common (if either station is out, the system is down). Tokyo/Narita has overcome this problem by installing two independent by-pass shuttles. In a bypass configuration, if one vehicle were to fail (assuming that it could be directed to the bypass and parked temporarily), the system could still maintain availability, thus providing greater availability than a single-lane configuration. As in the case of Singapore/Changi, breakdowns mean that passengers and employees either have to walk or take shuttle buses.

APMs are currently in use at fourteen airports in the United States today. See Appendix A which contains a complete list of all automated airport people mover systems in use around the world to-date.

TABLE 3.1 : Most Recent Automated Airport People Mover Systems (1988 - 1995)

Continent	Airports	Operational Configuration	Numbers	Distance (km)	System	Year	Syst Cost/km/pk pax
ASIA	CHANGI (T1 - T2)	Single lane shuttle	2	0.62	self-prop	1990	2600
ASIA	OSAKA - KANSAI	Dual lane shuttle	2	0.8	self-prop	1995	
ASIA	TOKYO NARITA - T2	Single lane bypass shuttle	2	0.28	cable	1992	4500
EUROPE	FRANKFURT MAIN	Pinch Loop	1	1.7	self-prop	1994	5945
EUROPE	LON-GATWICK,Syst 2	Dual lane shuttle	1	1.2	self-prop	1988	
EUROPE	LON-STANSTED	Pinch Loop	1	1.3	self-prop	1991	5120
EUROPE	PARIS - ORLY		1			1991	
NORTH AMERICA	CHICAGO O'HARE	Pinch Loop	1	4.4	self-prop	1993	6460
NORTH AMERICA	CINCINNATI	Dual lane shuttle	1	0.37	cable	1994	4040
NORTH AMERICA	DENVER	Pinch Loop	1	2	self-prop	1993	3590
NORTH AMERICA	DFW - TrAAm	Loop	1		self-prop	1991	
NORTH AMERICA	NEWARK	Pinch Loop	1	3.2	self-prop	1995	7360
NORTH AMERICA	PITTSBURGH	Dual lane shuttle	1	0.75	self-prop	1992	1685
NORTH AMERICA	TAMPA - LANDSIDE	Pinch Loop	1	1.1	self-prop	1991	

TABLE 3.2 : Existing Shuttle Configurations

Continent	Airports	Operational Configuration	Numbers	Distance (km)	Connection	System	Year
ASIA	CHANGI (T1 - T2)	Single lane shuttle	2	0.62	Inter-Terminal	self-prop	1990
ASIA	CHANGI - Airside	Single lane shuttle	1	0.57	Inter-Terminal	self-prop	
ASIA	CHANGI - Landside	Single lane shuttle	1	0.67	Inter-Terminal	self-prop	
ASIA	OSAKA - KANSAI	Dual lane shuttle	2	0.8	Intra-Terminal	self-prop	1995
ASIA	TOKYO NARITA - T2	Single lane bypass shuttle	2	0.28	Terminal to Gate	cable	1992
EUROPE	BIRMINGHAM	Single lane shuttle	1	1.25	Landside	maglev	1984
EUROPE	LON-GATWICK,Syst 1	Dual lane shuttle	1	0.3	Terminal to Gate	self-prop	1983
EUROPE	LON-GATWICK,Syst 2	Dual lane shuttle	1	1.2	Inter-Terminal	self-prop	1988
NORTH AMERICA	CINCINNATI	Dual lane shuttle	1	0.37	Intra-Terminal	cable	1994
NORTH AMERICA	LAS VEGAS	Dual lane shuttle	1	0.4	Terminal to Gate	self-prop	1985
NORTH AMERICA	MIAMI	Dual lane shuttle	1	0.4	Terminal to Gate	self-prop	1980
NORTH AMERICA	ORLANDO	Dual lane shuttle	3	0.58	Terminal to Gate	self-prop	1981
NORTH AMERICA	PITTSBURGH	Dual lane shuttle	1	0.75	Terminal to Gate	self-prop	1992
NORTH AMERICA	TAMPA - AIRSIDE	Dual lane shuttle	5	0.33	Terminal to Gate	self-prop	1971

TABLE 3.3 : Existing Pinch Loop Configurations

Continent	Airports	Operational Configuration	Numbers	Distance (km)	Connection	System	Year
EUROPE	FRANKFURT MAIN	Pinch Loop	1	1.7	Inter-Terminal	self-prop	1994
EUROPE	LON-STANSTED	Pinch Loop	1	1.3	Terminal to Gate	self-prop	1991
NORTH AMERICA	ATLANTA	Pinch Loop	1	1.9	Terminal to Gate	self-prop	1980
NORTH AMERICA	CHICAGO O'HARE	Pinch Loop	1	4.4	Landside	self-prop	1993
NORTH AMERICA	DENVER	Pinch Loop	1	2	Terminal to Gate	self-prop	1993
NORTH AMERICA	NEWARK	Pinch Loop	1	3.2	Landside	self-prop	1995
NORTH AMERICA	TAMPA - LANDSIDE	Pinch Loop	1	1.1	Terminal to Garage	self-prop	1991

The recently implemented APM at the new Denver International Airport (DIA) is an excellent example of how this technology can be used when long distances are involved. Figure 3.2 shows the layout of the passenger building facilities and the underground APM system at Denver, designed for an ultimate capacity of 110 million passengers per annum.

An underground APM, operating in a pinched-loop configuration, will link the main landside building with the four midfield concourses. The distance from the center of the landside to the APM station in concourse D (the most remote) is about 2 km. The design ultimate system capacity will be about 13000 pphpd with eight trains operating on headways of 1.8min(Leder 1991). This system provides for a high level of reliability through the following features [Lea & Elliot 1994] :

a) Dual-lane guideway with end-of-line and intermediate crossovers/switches to permit continued reduced service operations should a train or guideway component become disabled for a prolonged period

b) Sufficient number of spare vehicles to allow a comprehensive schedule maintenance program

c) Continuously available "hot standby train" which can replace a disabled train at short notice.

Passenger acceptance of APMs is generally very high. These systems are fully handicapped accessible. Passengers perceive the system to be safe and secure.

APMs require significant facilities : an exclusive right-of-way, stations, wayside equipment rooms, central control area, and vehicle maintenance facilities. Most are located on overhead structures or below-grade in tunnels. These systems require a relatively high level of maintenance. Through careful planning of facilities and operations, maintenance can be accomplished without impacting service.

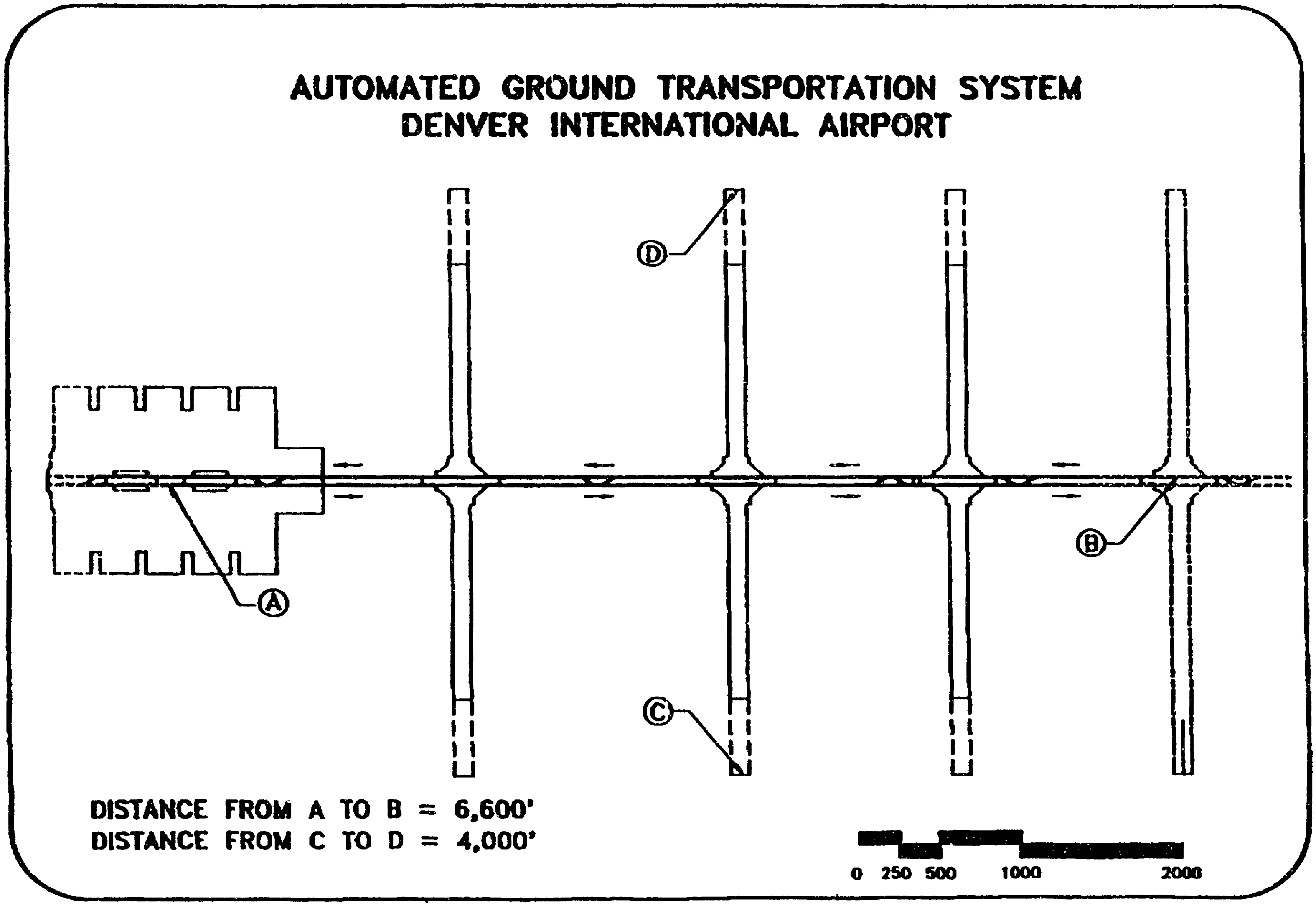


Figure 3.2 : Automated Ground Transportation System - New Denver International Airport

Generally, APMs are best suited for relatively high ridership over route lengths in excess of 300m, although shorter alignments in specialized situations should not be ruled out (e.g. Tokyo/Narita).

Many airport APMs are planned and designed for future expansion. For example, the "dashed lines" on Figure 3.2 show how the DIA passenger building facilities and APM guideway could be expanded to include a fourth airside concourse. Capacity can be increased by adding cars to trains and decreasing headways to a practical minimum of 90 seconds. Likewise, capacity can be reduced (e.g. during off-peak periods) by using fewer trains at longer headway intervals or by operating trains with fewer cars.

Another example of expandability would be the new Hong Kong/Chek Lap Kok airport where provisions have been made to be able to modify or extend the initial dual-lane shuttle system to that of a pinched-loop configuration in the future to serve the new midfield "X" -shaped concourse. Similarly with the new Kuala Lumpur International airport in Malaysia. The initial dual-lane shuttle system with two-car trains can be expanded to include an additional car in the future. Hence the length of the stations have been sized for this. At the same time, an additional ROW has been safeguarded in the tunnel for another independent shuttle system to serve the second "+"-shaped midfield concourse in the future [Lea & Elliot 1994].

Two main types of APM systems (see Table 3.1) currently in use at airports are :

a) **Self-propelled,** which is by far the most common;

b) **Cable-driven,** installed at Tokyo-Narita and Cincinnati in the United States [Momberger 1989, Fabian 1994].

Self-Propelled APM

The self-propelled APM performs well in both a shuttle mode over short distances and in a pinch-loop configuration over longer distances. It possesses the flexibility for expansion and will continue to perform well at high capacities over longer distances. For example, the system could be initially configured as a simple shuttle system over short distances in a small airport, but later modified or extended to a pinch-loop configuration when traffic volumes justify the expansion to a larger airport requiring multiple stops over increasing distances. High capacities can be achieved by decreasing the headways to as low as 90 sec and by adding more cars.

Self-propelled systems are however generally more expensive and complicated due to the more sophisticated train control and propulsion architecture. For example, additional collision controls, switching/failure mechanisms and special maintenance facilities are required for pinch-loop configurations. Moreover, all vehicles contain individual propulsion /drive components.

Cable-Driven APM

It is generally believed [AEG 1994, Lea & Elliot 1994, OTIS 1994, Tarassoff 1993, Venter and Fosbrook 1993, Wyss 1985] that the cable system has a lower capital and operating/maintenance(O&M) cost compared to the self-propelled because, being passive and thus lightweight and simple:

- lightweight guideway structure required
- concentration of system's main components in the drive room;
- lesser operating / maintenance equipment and spare parts required due to the simplicity of the technology
- less wear and tear as vehicle does not exert a driving force on the guideway

- no need for special maintenance facility as vehicles can be serviced on the guideway
- lower energy consumption

From a comparison of the system capital cost in Table 3.1 over the last 7 years, it is found that the average capital cost of the cable-driven technology in 1993 US dollars is \$4270 / lane-km / peak hour design passenger. This is about 10% lower than the \$4680 of the self-propelled technology and does not include the civil cost of the stations nor the guideways. Although no information is available on the O&M cost of the cable-driven technology, it can be deduced (from the above discussion) that there will be a cost reduction, but maybe not significant, because usually a large proportion of the operating cost comes in the form of employee wages - about the same number of staff are required to operate and maintain both the cable and self-propelled technologies. From the database, it is found that the average O&M cost per annual passenger trip for self-propelled system is about \$0.17 (in 1993 dollars), assuming a 5% yearly cost escalation rate. Appendix B tabulates the cost information for the existing systems.

Other advantages of the cable system include :

- easier to operate and maintain as the propulsion and controls are based on simple ropeway / elevator-type transportation technology applied over the century in many tramway installations. These are all stationary and centrally located at the passenger building.
- faster construction time
- good for short distance, direct point-to-point shuttle service of up to about 1.2 km
- unaffected by environmental conditions e.g. snow and ice as the vehicle is permanently attached to the cable and therefore does not depend on adhesion to the guideway surface
- provides a smooth, quiet ride due to the air cushion suspension system, thereby reducing air and noise pollution

On the other hand, the cable system has the following flexibility disadvantages :

- since the vehicle is attached to the cable, it cannot make the "crossovers" required for a pinched loop configuration, and therefore its application is limited to point-to-point shuttle service only. As a result, cable systems are generally not suitable over distances of more than a 1.2 km, or requiring multiple stops and high capacities. Being only of a shuttle configuration and possessing a lower overall speed as compared to self-propelled technology, its capacity is not only lower than that of similar self-propelled shuttles, but more importantly, decreases with distance because of the longer headways. Hence unlike the self-propelled, the cable-driven system has limited flexibility for expansion. Extending the cable shuttle system over longer distances even with the provision of additional cars will lead to unsatisfactory level of service and poor performance, as will be demonstrated in Chapter 7.1 of our analysis. Besides, the cable must be completely replaced if extension is required.
- In addition to poor performance, the system is mechanically not feasible over longer distances due to the length, weight of the cables required and power needed to drive the system.
- Impractical if significant horizontal or vertical curvature must be negotiated
- Cable has to be replaced around every three to five years due to wear and tear

3.2.2 **Shuttle Bus**

Buses are rubber-tired, driver-steered vehicles operating mostly on roads in mixed traffic conditions. At the airport, they typically operate over the aprons (to/from remote stands e.g. Washington Dulles), along passenger building frontage and circulation roadways on a non-exclusive basis, sharing the ROW with other vehicles. Speeds are highly influenced by roadway design, dwell time at stops and traffic/apron congestion. Given the low speed performance of airport roadways, vehicle design is usually not a constraining speed factor. Vehicle capacity for buses in airport service range between

20 to about 100 passengers. The largest buses cost in the region of around US$330,000 each [SATS 1995]. System capacity is a function of headway and individual bus capacity, and can vary widely from a few hundred to about 1500 pphpd [Leder 1991].

In general, passenger comfort is low, especially when buses operate at or near capacity. Passengers are also usually exposed to the elements of weather during the boarding and deboarding processes. Persons in wheelchairs and most other mobility impaired passengers find it inconvenient to use buses. Hence buses in general are considered by passengers to provide a low level of service.

3.2.3 **Moving Sidewalk**

A moving sidewalk is a conventional passenger carrying device on which passengers may stand or walk. Service is point-to-point along a straight alignment at a constant uninterrupted but low speed. Nominal lengths vary from 30 to 120m at a cost of around US$7800 to $9800 per metre [OTIS 1994]. Treadway widths typically range from 1 to 1.4m with the 1m width predominating. Moving sidewalk speeds are adjustable, but typically average 30m/min. Higher speeds are not recommended due to safety concerns. If passengers walk on the moving sidewalk at 60m/min, the resulting cumulative speed will be 90m/min (5.4km/hr or 3.4mph).

Moving sidewalk capacity is a function of speed and passenger density on the treadway. For a 1m treadway width, a speed of 30m/min and 0.23 m^2 per standing passenger, the calculated system capacity is 7800 pphpd [Leder 1991]. Some suppliers suggest higher capacities with greater passenger densities, however, 0.23 m^2/pax is considered to be a practical minimum, especially if carry-on articles are included. Given slight pauses in boarding moving sidewalks and greater space for those who walk rather than ride, a practical maximum system capacity is at most 4500 to 5000 pphpd.

Moving sidewalks with standard 1m treadway width generally do not perform well with mixed standing and walking traffic. This limitation is especially significant in an airport environment because of carry-on articles most passengers have with them. For standees, these items are typically placed on the moving sidewalk next to the passenger. This makes passing by walkers, many of whom also have carry-on articles or luggage in their hands, very difficult. Operating parallel moving sidewalks in the same direction, as in the United Airlines terminal at Chicago/O'Hare and at the new Denver International Airport, allows segregation of those wishing to walk from those wishing to only ride.

Other advantages and disadvantages of moving sidewalks include :

- Access is continuous over time. Thus frequency of service is not a factor, unless there is a queue at the entry point where passengers pause when transitioning to the moving sidewalk.
- Maintenance of moving sidewalks is not complex and can best be accomplished at night or during off-peak periods. Any system stoppage during periods of terminal activity can cause major inconvenience to passengers, who must walk long distances.
- Persons in wheelchairs and most other mobility impaired passengers are not able to use moving sidewalks.
- Moving sidewalks because of their orientation and point-to-point nature, can be an inconvenient barrier to cross-concourse passenger movements. It is often necessary to walk around the end of a moving sidewalk and /or backtrack to one's destination.

Leder [1991] suggests that moving sidewalks, in general, can be used to aid passenger mobility when the total length of passenger movement does not exceed the nominal range of 300 to 450m. Slow speeds of 30 m/min and the tendency to form barriers to cross travel movements are distinct drawbacks.

3.3 Baggage Transport System Technologies

Baggage handling systems must be designed with sufficient capacity and flexibility to cope with significant increases and variations in peak volumes and future growth. Airport passenger buildings will continue to require improved baggage handling systems to reduce time delays, losses and costs in processing bags. Along with the rate of increase in baggage handling, the average transportation distance for bags will also continue to increase as passenger buildings increase in size to accommodate more passengers and aircraft. Since automated people mover systems have become an almost indispensable part of the airport to facilitate the transport of passengers, passengers expect a compatible and equal baggage handling system. Its efficiency governs the reporting time of passengers. Lost of late arriving bags incurs passengers inconvenience and loss of goodwill. Therefore baggage should move at the same speed or slightly faster than passengers. In other words, baggage systems should match the capability and service levels provided by the availability of automated people movers.

Unlike passengers, baggage is not "inconvenienced" by traveling long distances. But rather, the delivery times and reliability become important issues when assessing the potential performance of baggage operations. Of these two issues, delivery times are directly influenced by the geometry of the terminal configuration. Reliability is more likely to be affected by issues such as the level of automation, the degree of redundancy in the system and the manpower methods in place.

Figure 3.3 illustrates a general sequence of baggage flow throughout the airport system. Baggage can be placed into different categories for the purpose of determining travel / delivery times, namely :

- Terminating (inbound) baggage
- Originating (outbound) baggage
- Normal transfer baggage
- Ramp transfer (short connection) baggage

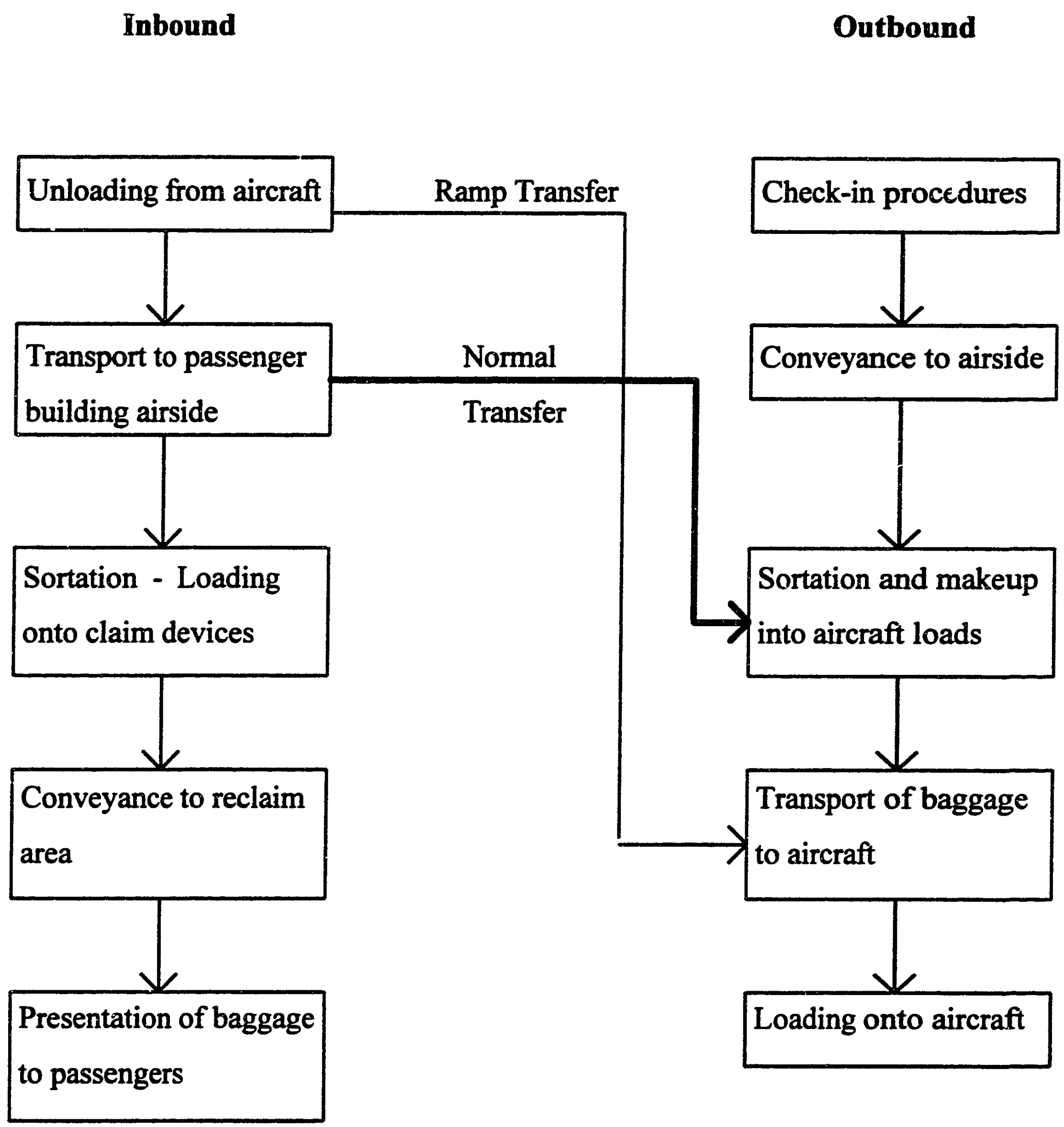


Figure 3.3 : General Flow of Baggage

Terminating baggage

A general sequence for terminating or inbound baggage is illustrated in the left column of Figure 3.3. Baggage is first unloaded from the aircraft onto tug and cart / dollies(for containerized baggage), which then transport the baggage to a sortation room typically located within the passenger building where it is loaded onto reclaim devices so that passengers can retrieve it.

Originating baggage

A general sequence of originating or outbound baggage is illustrated in the right column of Figure 3.3. Baggage is sent generally by conveyor belt from check-in to the baggage sortation room. At the sortation room, bags are sorted either manually or mechanically onto tug and carts / containers(for wide-bodies), which are then transported to the aircraft to be subsequently loaded.

Normal transfer baggage

Transfer baggage is unloaded (along with terminating bags) from the aircraft and transported to the sortation room where it is separated by destination and / or departing flight numbers. They are then put into carts / containers (along with originating bags) and transported to the departing aircraft for loading. Even if the arrival and departure gates are adjacent, transfer bags are generally taken back to the sortation room before it is transported to the departing aircraft.

Ramp transfer baggage

Also known as short connection baggage, ramp transfer baggage is taken directly from the arriving aircraft to the departing aircraft(s), often by tug and cart. One common way for baggage to become designated as "short connection" bags is through flight delays. A late arrival into a station can cause delays for downstream connecting flights that are frequently held up until passengers and baggage are transferred. Passengers can often sprint from their arrival gate to their departure gate. Normal transfer bags, however, would follow the sequence above. To save time, short connection bags are loaded directly onto tug / cart, transported and loaded onto aircraft. On the other hand, ramp transfer operations can also be "created" during the flight scheduling process. If a close connection is advantageous to an airline for competitive reasons, it may be willing to incur the additional costs associated with operating additional tug and carts. Many important hub airports, such as the United Airlines terminal at Chicago/O'Hare and the USAir facility at Pittsburgh rely on ramp transfer operations to deliver bags with short connection times of less than 30 mins [UA 1994, BNP 1994b].

Sortation

The sortation at an outbound bag room can be described as manual, semi-automated, or fully automated. The level of automation is usually determined by the volume of bags to be handled, the nature of the traffic, the design of the check-in operation and the delivery time standards set by the airlines or operator. One of the aims of automated sortation is to achieve flexible distribution of any bag from any check-in or transfer input location to any make-up device, and to reduce the possibility of "mis-sorts" due to manual sortation [BNP 1994a] .

Manual systems are the simplest. Bags are conveyed from the check-in area to the bagroom where their destination or flight tags are read by human operators and sorted onto the appropriate bag carts / containers. In semi-automated systems, flight tags on departing bags are read by human operators who punch the tag code into a computer. The bag is then tracked and diverted / tipped by pusher diverters / tilt-tray sorters from a central conveyor to a designated makeup device where a human operator then places the bag onto the appropriate bag cart or container (wide bodies). Fully automated systems use laser readers and bar-coded bag tags to replace the human operator in the first step of the sortation process. Differences in sortation times (based on the level of automation) arise from differences in the time it takes to identify and divert the bags to the appropriate cart. The sortation time also depends on the number of bags for that particular flight as well as the number and size of other flights at the airport.

Centralized versus Decentralized Bagrooms

Centralized baggage sortation rooms are the most common approach to outbound baggage handling at airports today. Table 3.4 lists some of the most recent baggage systems over the last seven years and Appendix C tabulates existing centralized bag systems.

Centralizing the baggage operation maximizes labor and equipment productivity through cross-utilization of staff and equipment, potentially lesser area utilization requirements, and concentrated supervision and control. The average capital cost of the system per design peak hour bag in 1993 US dollars is about $3000 (derived from list of cost of systems at Appendix E)

Due to the expansion of airports, aircraft gates are becoming more distant from centralized bagroom operations, resulting in longer flight close-out times. This is unacceptable for modern hub airports, such as the new Denver International and Pittsburgh airports. These have decentralized the baggage sortation rooms within the midfield concourses in an effort to bring them closer to the aircraft and reduce the tug/cart travel distances (see Table 3.4). This potentially increases the cost of the system due to duplication of equipment and manpower in each and every bagroom. The new USAir facility at Pittsburgh consists of a decentralized multiple bagroom operation where baggage for every six gates are handled / sorted at a mini-bagroom. On the other hand, the United Airlines concourse at the new Denver International airport has a fully decentralized (distributed) baggage system where bags are processed at every gate. This was made possible by the implementation of a track-mounted single-bag destination coded vehicle (DCV) system that transports and automatically sorts individual bags from check-in to the respective make-up device at the gate. Appendix D lists some of the existing decentralized bagroom systems today.

TABLE 3.4 : Some Recent Airport Baggage Handling Systems (1988 - 1995)

Continent	Country	Airports	Terminals	Bagroom	Sortation	Transport System
ASIA	JAPAN	OSAKA- KANSAI		Centralized	Auto Tilt-Tray/Manual	Tug and Cart
ASIA	SINGAPORE	CHANGI	T1	Centralized	Manual	Tug and Cart
ASIA	SINGAPORE	CHANGI	T1 / T2			Telecar
ASIA	SINGAPORE	CHANGI	T2	Centralized	Auto Tilt-Tray	Tug and Cart
AUSTRALIA	AUSTRALIA	SYDNEY		Centralized	Auto Pusher	Tug and Cart
EUROPE	BELGIUM	BRUSSELS		Centralized	Auto Tilt-Tray	Tug and Cart
EUROPE	FRANCE	PARIS - CDG	T2 C and M	Centralized	Auto Tilt-Tray	Tug and Cart
EUROPE	GERMANY	MUNICH	T A,B,C,D,Z	Decentralized	Auto Tilt-Tray	Tug and Cart
EUROPE	NETHERLANDS	AMS-SCHIPHOL	T West	Centralized	Auto Vertisorter/Manual	Tug and Cart
EUROPE	UNITED KINGDOM	LON-HEATHROW	T3	Centralized	Auto Pusher	Tug and Cart
EUROPE	UNITED KINGDOM	LON-HEATHROW	T4	Centralized	Auto Tilt-Tray	Tug and Cart
EUROPE	UNITED KINGDOM	MANCHESTER	T2	Centralized	Auto Tilt-Tray	Tug and Cart
NORTH AMERICA	UNITED STATES	BOSTON	AMERICAN	Centralized	Auto Pusher	Tug and Cart
NORTH AMERICA	UNITED STATES	CINCINNATI	DELTA	Decentralized	Auto Tilt-Tray	
NORTH AMERICA	UNITED STATES	DENVER	UNITED	Decentralized	SBDCV	SBDCV
NORTH AMERICA	UNITED STATES	NEW YORK JFK	AMERICAN	Centralized	Auto Pusher	Tug and Cart
NORTH AMERICA	UNITED STATES	PITTSBURGH	USAir	Decentralized	Auto Pusher / Manual	High Speed Convey

On the whole, most large airports employ the centralized bagroom concept with automated sortation by either pusher diverters (in the United States) or by tilt-tray sorters (in Europe and Asia), followed by conventional tug/cart system as the main form of transport delivery to the aircraft. However, newer and larger airports having midfield concourses separated a distance from the landside building have chosen to adopt higher speed systems such as conveyors at Pittsburgh, DCVs at Denver, multi-bag carts (telecar) at Atlanta as the main form of transport, with subsequent automated sortation (by tilt-trays, pushers, DCV) to partially or fully decentralized bagrooms for processing. Thereafter, the bags are manually delivered by tug/carts to the aircraft.

Hence various baggage handling alternatives exist which can serve all passenger building configurations, but their cost and complexity varies with the distance from the landside building to aircraft gates, the volume to be handled, and the ability to meet the performance standards set. As different airports have different needs, each must be analyzed for its own requirements. The best baggage system is the one that meets up with the demands of physically moving the bag to keep up with the passenger, and possesses the flexibility for future expansion.

A description of the main baggage transport technologies more commonly in use today and possibly in the future follows.

3.3.1 **Automated multi-bag cart system**

The multi-bag cart system, known as the telecar system, has been installed in only two systems around the world [BNP 1990], namely :

a) Atlanta, between the landside building and Delta (formerly Eastern) Airlines concourse for originating and terminating bags;

b) Singapore/Changi, between terminals 1 and 2, with a possible future extension to serve the new terminal 3 building [WH Pacific 1995]. This system is used for the transport of interline inter-terminal bags (See Table 3.5).

The telecar system is essentially a high-speed point-to-point system for general transport only with no capability for sortation. The carts, each capable of carrying between 8 to 12 bags, are propelled by Linear Induction Motors along tracks at a top speed of about 32 km/h, roughly four times the speed of high speed belt conveyors. In both the existing systems, the carts are manually loaded.

In Atlanta, originating bags are conveyed from check-in into one of the two baggage make-up units, where they are then manually transferred to a cart and dispatched to the concourse when full or on a time-interval basis [Klingen 1978]. Similarly, for Singapore/Changi, transfer bags arriving in say terminal 2 that are destined for terminal 1 are sorted within the terminal 2 outbound system to the pier / lateral adjacent to the telecar load station. Here, the bags are manually loaded onto the carts and dispatched to terminal 1. Unloading for both the Atlanta and Changi systems is accomplished either manually or by a pusher which automatically sweeps through the cart, unloading bags to a take-away conveyor which then conveys the bag to an outbound sortation system. The unload stations are usually staffed on a monitoring level to clear jams.

Table 3.5 : Existing Telecar and DCV Systems [BNP 1990]

Airports	Singapore/Changi	Atlanta	Denver	San Francisco
Terminal	T1 / T2	Delta	United	United
Transport System	Telecar	Telecar	DCV	DCV
No. of Vehicles	20	80	3800	184
Track Length (km)	2.5	?	32	2.0
Year of Operation	1990	1981	1995	1975

Advantages of the telecar include the ability to provide high capacity, reliability and oversized baggage handling capability. Its downside is the need for a relatively high degree of manual interaction required to load / offload (very often) and to monitor the system. As the telecar does not possess the sortation capability, additional delivery time is required. Moreover, as with all automated systems which are "prone" to failures, a "back-up" tug and cart system is required. This adds to the cost of an already expensive system costing anywhere in the range of US$8000 to $10000 per linear metre of track (includes vehicles) [WH Pacific 1995].

3.3.2 **Automated Single-bag Destination Coded Vehicle system**

The single-bag destination coded vehicle system, known as the DCV system, is in operation at two major airports in the United States today : the United Airlines facilities at San Francisco (SFO) and the new Denver International Airports (see Table 3.5). To many, the system at SFO is a misapplication of the DCV technology, since the proximity of check-in to the outbound system does not warrant a high speed transport system. The system is also not used for sortation. In Europe, a single bag type of system is in operation at Frankfurt Main International Airport in Germany. Table 3.6 gives a brief background of the history of the DCV in the United States.

The DCV system recently implemented at the new Denver International Airport (DIA) is the automated (dynamic) load/unload concept, developed to accomplish both high speed transport as well as sortation of baggage. The concept involves taking the existing technology of DCV such as that at UAL-SFO or Frankfurt-Germany, and instead of using an insert or tub assembly, a tilt-tray assembly is placed on top of the vehicle. The resulting DCV is capable of both high speed transport, and of being loaded and unloaded in the same manner as a tilt-tray sorter for the sortation of individual bags. This is the

Table 3.6 : Brief history of the DCV in United States [BNP 1990]

Owner /Location	Service Start Date	Length of service/year	Supplier	Comments
UAL - DIA	1995	N/A.	BAE	High Startup Delays
UAL - SFO	1975	N/A.	BAE	High maintenance costs
Braniff - DFW	late 60's	4	Docutel	Operational maintenance problems
SEA - TAC	late 60's	1988	Rexnord	GTS system, noted for vibration problems, never performed as expected
American - DFW	early 70's	?	Docutel	Operational Maintenance problems
PanAm - JFK	late 60's	3	Docutel	Operational Maintenance problems

primary advantage of a DCV over a telecar system. It also allows for a more continuous flow operation as compared to the batch service provided by the telecar, thereby potentially minimizing delivery times.

Disadvantages of the DCV include high development risk associated with systems larger and more complex than those already in operation, extremely high cost of about US$10000/m track (excluding vehicles, costing about $10000 each at 1993/4 prices) [BNP 1994a], and the lack of oversize baggage handling capability which necessitates another independent system such as the telecar or tug/cart. In any case, a tug/cart system will normally be required as a "back-up" for such complex automated systems.

3.3.2 **Tug and Cart**

The tug and cart is the most basic and commonly used system and often serves as the main form of transportation of bags between the passenger building and aircraft and vice versa. It is used widely in most airports today, including major airports such as Chicago/O'Hare, Amsterdam/Schiphol, London/Heathrow and Singapore/Changi (see Table 3.4).

Originating bags are generally manually loaded at the main passenger building after make-up, into tug and carts (or containers for wide-bodies) and delivered to the aircraft. Similarly, terminating bags are off-loaded from aircraft and delivered to the main passenger building before being manually off-loaded onto conveyors to claim devices.

The advantages of a tug and cart system include, minimal capital costs of equipment (US$29000 per tug and $3500 per cart at 1993 prices) [BNP 1990], high throughput capacity, reliability, and oversized baggage handling capabilities. More importantly, it serves as a "back-up" system for the automated alternatives discussed above. On the other hand, its disadvantages are the high operating and maintenance costs in the form of wages for drivers / baggage handlers and upkeep of equipment, and generally longer delivery times than the automated systems over increasing distances (as demonstrated in Chapter 7.2) due to its lower speed capability, especially along congested apron roadways.

CHAPTER 4 - ASSUMPTIONS

4.1 Airport Passenger Building Configuration and Geometrical Representation

This study looks at three cases : a smaller airport, a larger airport, and expansion from a small to a larger airport due to traffic growth. A smaller airport would consist of a medium-sized 15 to 20 million passengers per annum(mppa) passenger building facility with 28 gates; and a larger airport, 30 to 40 mppa served by 56 gates. This represents a ratio of 1.6 gates per million passengers which is not uncommon in existing and proposed major international airports such as, the new Hong Kong/Chek Lap Kok airport, Second Bangkok International Airport, new Seoul, newly-opened Osaka/Kansai Airport, and Singapore/Changi where the fleet mix consists of up to 70% wide-body aircraft [Greiner 1993, Bechtel 1993, Aeroport de Paris 1993].

To establish the sensitivity of our findings to a different gate/passenger ratio, a comparison is made with an alternative gate/passenger ratio of 2.8. This could be representative of airports whose predominant aircraft type is narrow-body. For this case, smaller and larger airports are assumed to handle 10 and 20 million passsengers respectively.

To represent what we think would be the design of possible airport passenger building configurations of the future, we have selected four concepts for study; namely,

a) Midfield Linear

b) Midfield "+"

c) Hybrid Centralized Linear with Midfield Linear

d) Hybrid Centralized Pier with Midfield "X"

In order to compare and contrast the different configurations, it is necessary to standardize the concept types so that differences in performance estimates come from the geometry inherent in each concept.

The "pure" midfield linear (see Figure 4.1) and "+" configurations (Figure 4.2) would consist of a main landside passenger processing block connected underground (below taxiways) to midfield linear and "+" concourses respectively. Unlike the linear concourses, the "+s" would be offset from the extended central axis of the passenger building.

The hybrid centralized linear with midfield linear configuration (see Figure 4.3) differs from the pure midfield linear through the addition of a linear concourse adjacent to the landside processing facility to facilitate largely short-haul originating and terminating business traffic. Similarly, the hybrid centralized pier with midfield "X" concept (Figure 4.4), as the name suggests, would consist of additional parallel pier concourses adjacent to the landside building. The "Xs" in this case, unlike the pure midfield "+" concept, would lie along the extended center line of the main passenger building.

A smaller 28-gate airport will consist of a landside building (with an adjacent attached concourse in the case of hybrid concepts) and a midfield concourse. For the hybrid concepts, the landside concourse is assumed to have eight aircraft stands, whilst the midfield has twenty. A larger airport will include an additional midfield concourse for 28 gates, making a total of 56 gates for all configurations.

To provide a consistent platform for comparing and contrasting the different terminal configurations, the following assumptions are made :

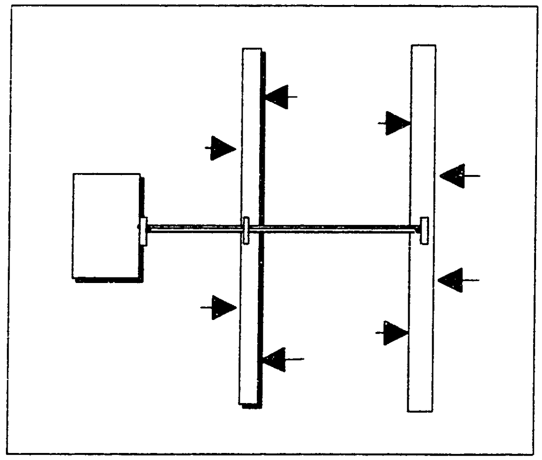


Figure 4.1 : Midfield Linear Configuration

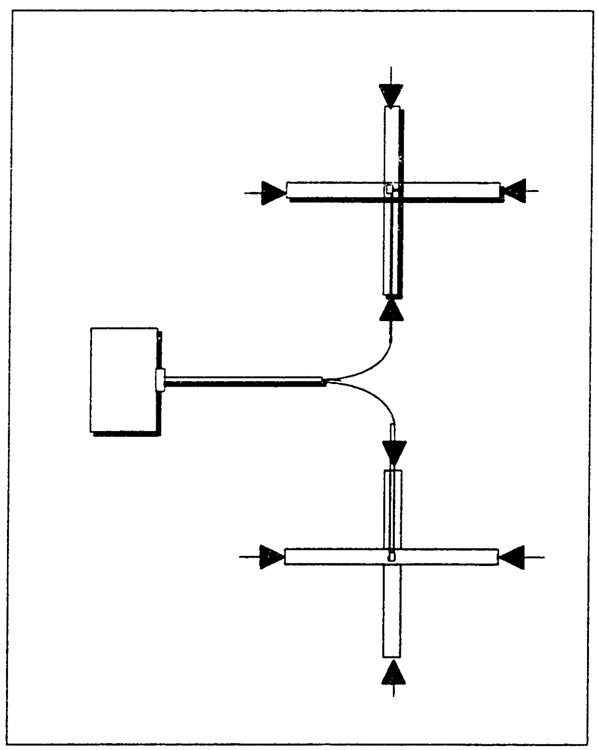


Figure 4.2 : Midfield "+" Configuration

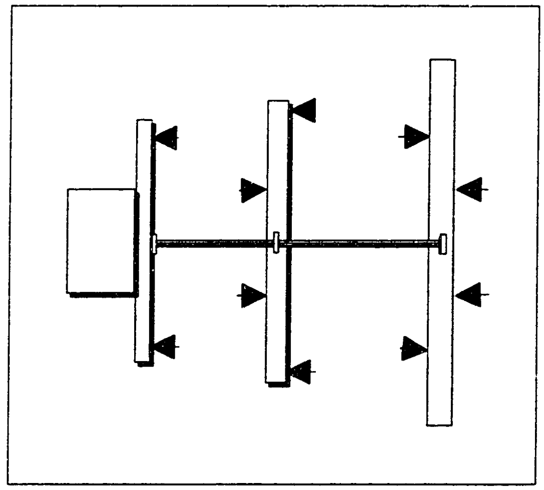


Figure 4.3 : Hybrid Centralized Linear and Midfield Linear Configuration

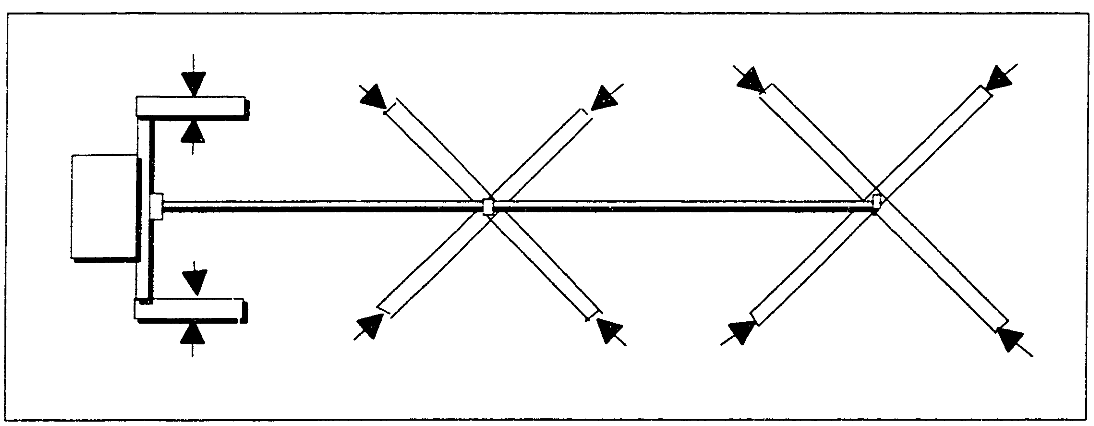


Figure 4.4 : Hybrid Centralized Pier and Midfield "X" Configuration

a) Aircraft Characteristics and mix

Table 4.1 shows the aircraft mix and ICAO characterization that is assumed based on recent designs at major and new international airports e.g. Hong Kong/Chek Lap Kok, Singapore/Changi, Second Bangkok. The weighted average aircraft wingspan is 53.75m, and assuming a 7.5m wingtip clearance (ICAO requirement), the weighted average gate spacing is about 60m.

b) Characteristics of Landside Building and Midfield Concourses

- Dimensions of landside building : 300m wide by 135m deep
- Concourse Width : 24m, 45m for single and double-loaded concourses respectively
- 90 degree angle between the arms of "X / +" concourses
- 122m (400ft) radius for underground connection of midfield "+" concept

c) Airfield Characteristics

- dual taxiways are provided between concourses to facilitate aircraft maneuverability
- ICAO category F aircraft used as the design aircraft to determine airside separation requirements with the exception of cul-de-sacs where design aircraft is category E.
- 10m wingtip clearance between taxiing aircraft and object, and 7.5m between parked aircraft.
- 10m wide apron service road surrounding all concourses

From the above assumptions, we derive the distances between the landside building and midfield concourses for the various configurations, as presented in Table 4.2.

Table 4.1 : Aircraft Mix Assumed for the Analysis

Aircraft Category (ICAO)	Aircraft Mix (%)	Wingspan(m)	Seat Capacity
F	5	86	800
E	25	65	400
D	50	52	280
C	20	36	140

Table 4.2 : Travel Distances between Landside Building and Midfield Concourses for Various Configurations

Passenger Buildings	Midfield		Hybrid Centralized/Midfield	
	Linear	"+"	Linear	Pier / "X"
Landside & 1st midfield concourse	340	1056	433	585
1st & 2nd midfield concourses	455	N/A.	455	628
Landside & 2nd midfield concourse	795	1056	888	1213

4.2 **Estimating Walk Distances and Area requirements**

Average Walk Distance is determined by the distribution of passengers which is in turn influenced by the utilization of aircraft stands within an airport. If no information is available, it may be reasonable to assume that the size and utilization of each gate in an airport is the same. The average walk distance is then simply "half" the concourse length, depending on the geometry.

However, intelligent airports practice preferential gate assignments, particularly for larger aircraft e.g. Jumbos. These are placed closer to connections to improve service for most of the passengers. This leads to an uneven distribution of aircraft capacity gates and of passengers. This in turn affects the probability of passengers arriving or departing from those gates. For example, in a midfield linear concept where there is minimal geometrical constraints, larger aircraft would be assigned to gates closer to the center of the concourse in an effort to minimize walk distances for the majority of passengers. This is exactly the plan for the new Denver International Airport for example.

On the other hand, some designs do not permit this intelligent assignment of aircraft and passengers. For example, in a midfield "+" concept where there is severe geometrical constraints within the cul-de-sacs, larger aircraft are "forced" to be assigned to the outermost gates near/at the ends of the concourses. This inevitably creates longer average walk distances for the passengers.

The general expression for the average walk distance of originating and terminating passengers is given as:

$$\bar{d} = \sum_{j=1}^{G} d_{ej} p_{ej}$$

where d_{ej} = absolute distance between entrance e and gate j

p_{ej} = probability of passengers traveling between entrance e and gate j,

where $$p_{ej} = \frac{s_j}{\sum_{j=1}^{G} s_j}$$

s_j = seat capacity of aircraft at gate j

G = total number of gates

Using the above aircraft mix and applying the preferential gate assignment techniques described above consistently across the various configurations, one can derive both the average and maximum walk distances. The average is determined by using the above formula for each of the concourses for a particular configuration, and then weighted according to the total aircraft gate(seat) capacity at the respective concourses to arrive at an overall average for that configuration. The maximum walk distance is taken simply as the distance to the most extreme gate. In this study, we are assuming that the passenger walk distances are equivalent to the travel distances for the transportation of inbound and outbound baggage. This assumption is valid as we are assuming that the number of bags carried per passenger does not depend on the gate. We are also assuming that no moving sidewalks are provided along the concourses.

Based on the total aircraft gate capacity at each concourse, one can estimate the proportion of total passengers or baggage demand (load) to be accommodated at each concourse for a given configuration. Table 4.3 summaries the walk distances and load distribution for the different airport passenger building configurations, assuming that no walking is required between the main passenger building and concourses. Both Tables 4.2 and 4.3 are used as inputs to the model described in Chapter 5 to determine the performance of a given combination of technology and configuration.

Table 4.3 : Summary of Walk Distances(m) and Load Distribution of Different Passenger Building Configurations for Originating and Terminating Passengers

Configurations	Smaller Airport - 28 gates			Larger Airport - 56 gates		
	Avg.	Max.	Load (%)	Avg.	Max.	Load(%)
Midfield Linear						
• midfield concourse	191	426	100	191	426	50
• 2nd concourse	N/A.	N/A.	N/A.	191	426	50
• Overall (including terminal)	326	561	100	326	561	100
Midfield "+"						
• midfield concourse	207	270	100	207	270	50
• 2nd concourse	N/A.	N/A.	N/A.	207	270	50
• Overall (including terminal)	342	405	100	342	405	100
Hybd. Centralized Linear/Mid.Linear						
• centralized concourse	118	247	36	118	247	18
• midfield concourse	134	273	64	134	273	32
• 2nd concourse	N/A.	N/A.	N/A.	191	426	50
• Overall (including terminal)	283	432	100	316	585	100
Hybd. Centralized Pier / Mid. "X"						
• centralized pier	236	292	34	236	292	17
• midfield "X"	170	211	66	170	211	33
• 2nd "X"	N/A.	N/A.	N/A.	207	270	50
• Overall (including terminal)	347	439	100	357	439	100

The results show that the average walk distances for both the "X" and "+" configurations are greater than that of the linear configurations. This is due to the inherent difficulties associated with the "X / +" geometry which rarely permits larger aircraft types, e.g. B747s, to be parked within the cul-de-sacs due to the space constraints. Figure 4.5 illustrates the "unusable/wasted" space within the corners of the cul-de-sacs in which aircraft cannot be parked without suffering severe maneuverability problems. Therefore larger aircraft are usually assigned to the gates at the extreme ends of the piers for easier maneuverability. This has the effect of increasing the average walk distance for passengers as a greater proportion of passengers must traverse longer distances as compared to the linear configurations to get to the larger aircraft at the ends of the piers.

Under the linear concourse arrangement, given the lesser space constraints and thus higher flexibility to practice intelligent gate assignments, larger aircraft are expected to be assigned to gates closer to the center of the concourse. This has the effect of minimizing the average walk distances for a greater proportion of passengers. On the other hand, the maximum walk distance is more than that of the "X / +" as aircraft are distributed along only two sides of a linear concourse as opposed to 8 sides of an "X / +".

Area requirements

Table 4.4 presents the passenger building and total land area requirements for the different airport configurations. Passenger building area is defined here as the area occupied by passenger buildings including the main processing building, and the aircraft parking areas. In other words, it is the rigid pavement or "concrete" areas. Total land area is the passenger building area plus the taxiway systems between the concourses. It does not include the parallel taxiway systems adjacent to the Runways.

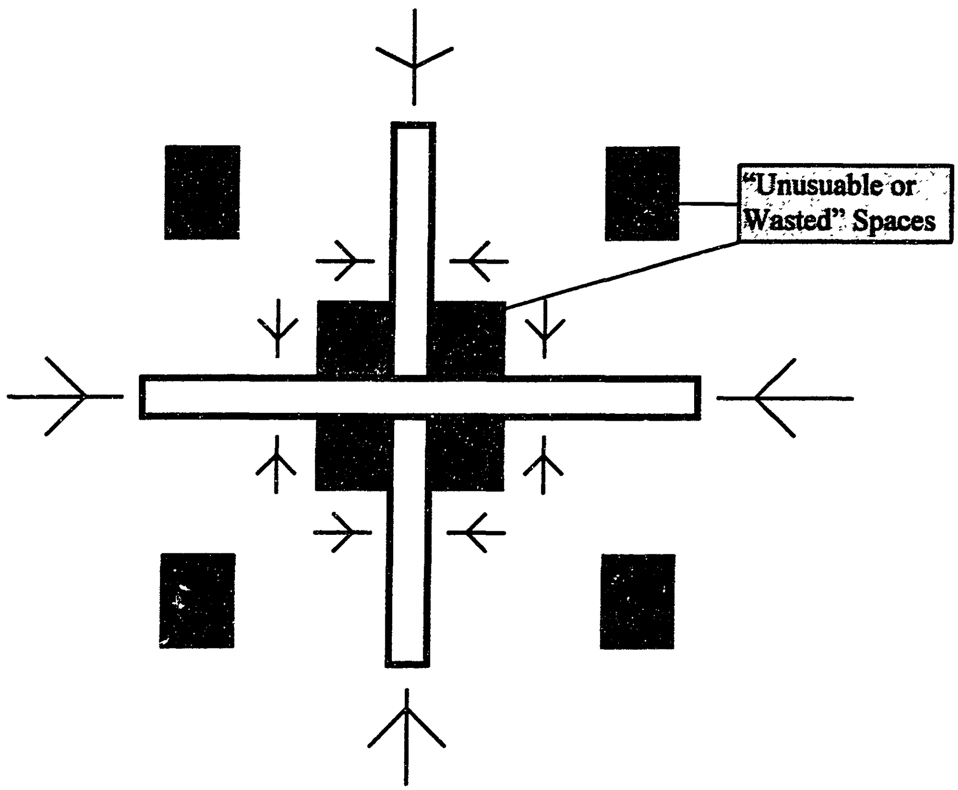


Figure 4.5 : "Unusable" spaces within cul-de-sacs of an "X / +" configuration

Table 4.4 : Comparison of Area requirements for Different Airport Passenger Building Configurations for 56-gate Airport

Description	Midfield		Hybrid Centralized/Midfield	
	Linear	"+"	Linear	Pier/"X"
a) Passenger Building, including Aircraft Parking Area (hectare)	48.9	116.6	47.7	62.5
b) Area per Gate (hectare) ((a) / 56gates)	0.87	2.08	0.85	1.12
c) Depth between Runways (m) (does not include adj.parallel taxiways)	874	1744	874	529
d) Length of Airfield Required (m)	1057	1119	1174	1709
e) Total Land Area (hectare) ((c)*(d) = (a) + apron taxiway systems)	92	195	103	90
f) Total Land Area per Gate (hectare) ((e) / 56gates)	1.65	3.48	1.83	1.61
g) Passenger Building Area / Total Area ((a) / (e))	0.53	0.60	0.46	0.69

Both the Hybrid Centralized Linear with Midfield Linear (HLL) and Midfield Linear (ML) configurations make very efficient use of the land allocated for aircraft parking and passenger buildings with the HLL requiring slightly less. The Hybrid Centralized Pier with Midfield "X" (HPX) configuration requires about 30% more "concrete" area as a greater amount of space is "wasted" within the cul-de-sacs (see Figure 4.5) as explained above even though the depth between the Runways is reduced. Another consequence of the wasted space in an "X" is the longer travel distance from the main passenger building as compared to the linear configurations. This means that a greater airfield length is required.

The Midfield "+" configuration (M+) requires significantly more space for passenger building and aircraft parking, double that of the HPX configuration. This is primarily because a "+" requires significantly more area than an "X".

From the total land perspective which includes not only the passenger building and aircraft parking areas but also the dual apron taxiway system between the concourses (assume that Runway separation is dictated by longest concourse length), Table 4.4 shows that the HPX concept requires slightly lesser total land area, marginally lower than the ML and about 12% less than the HLL configuration. Since the separation between the Runways is significantly greater in the HLL/ML, the total area of the dual apron taxiway systems between their concourses will naturally be greater than that of the HPX. So on the aggregate, it is found that even though less "concrete"area is needed under the HLL/ML configurations, their additional apron taxiway systems results in slightly larger overall land areas compared to the HPX concept. Nevertheless, since concrete construction is significantly more expensive than flexible pavement construction (of taxiways), it is envisaged that the HLL and ML configurations could potentially be cheaper on the whole as compared to the HPX concept.

Calculations for the M+ concept show that it continues to require the most overall land area amongst all configurations, double that of the others. This is due to the significantly larger area required between the runways to accommodate the "+s" (which are offset from the extended center of the main terminal) and often the taxiway system between the "+s". New proposed international airports at Kuala Lumpur and Bangkok have chosen to adopt configurations somewhat similar to this.

Runway Separation Constraints

There may exist geographical constraints which limit the maximum concourse length in one direction e.g.. Runway separation constraints. In this case, a configuration with two "X"-shaped concourses might be compared to one with three parallel (instead of two) concourses having the same maximum length (while keeping the total number of gates constant). Since the linear concourses can be positioned closer together due to their shape, the latter configuration would require less total land area, making it more attractive in terms of real estate costs. Calculations show that a HLL configuration with three shorter linear concourses instead of two (assumed in this thesis) would yield a total land area of 84 hectares as opposed to the HPX of 90 hectares (a 7% reduction).

Other considerations

Movement of aircraft in an "X or +" configuration is not as efficient as the linear due to the cul-de-sacs. This could give rise to more congestion delays especially during peak periods as aircraft will have to "wait" for each other before entering / exiting..

Another disadvantage of the "X / +" is the limited ability to lengthen the piers to accommodate higher traffic levels. This is because the "X / +" is constrained on all four ends by taxiways that are usually already in place. On the other hand, land is normally safeguarded for the possible lengthening of linear concourses.

4.3 General Assumptions

This study considers mainly the originating/terminating (OD) traffic and interline traffic which is assumed to constitute only a small portion of the traffic (such passengers backtrack to/from the landside building for processing). On-line traffic is not considered in our analysis as the primary focus is on the point-to-point people mover and baggage transport technologies between the landside passenger building and the airside concourses. We are assuming that 70% and 10% of the total traffic are OD and interline respectively; these will use the people mover and baggage transport systems. The remaining 20% are assumed not to use the systems provided.

The study assumes that 6% of the daily traffic occurs during the peak hour in the major direction, and 40% of this during the peak 15 min period for terminating traffic to account for the surge effects of simultaneous arrivals. As the originating traffic is generally not as "peaky", we assume that 30% occurs during the peak 15min. The analysis of passengers only considers the more critical case i.e. terminating traffic. The originating traffic is included in the assessment of the baggage systems as the establishment of flight close-out times at airports largely depends upon the delivery times of the last departing bag.

Based on the assumed aircraft fleet mix(Chapter 4.1), average load factor of 75%, and 80%(OD+interline) traffic, the study estimates an average aircraft load of 185 passengers and 277 bags (assuming 1.5bags/pax) will use the transport systems to/from the landside building. This is equivalent to seven forty-bag containers or two trains of tug and carts/containers (3 to 4 carts per tug is common at many airports).

Table 4.5 gives the range of loads under consideration for each of the two airport sizes based on the above general assumptions. These loads are apportioned to the concourses based on the total aircraft gate(seat) capacity at the respective concourse. Table 4.3 gives the load distribution amongst the concourses for the different passenger building configurations.

Table 4.5 : Range of loads under consideration for the two airport sizes

Traffic Type	Smaller Airport		Larger Airport	
Annual traffic (mppa)	15	20	30	40
In peak 15 min :				
Terminating pax load (pax/min)	50	75	100	150
Terminating bag load (bag/min)	75	100	150	200
Originating bag load (bag/min)	50	75	100	150
Terminating flights	4	6	8	11

4.4 People Mover Approach and Assumptions

For a smaller airport, the following technologies are compared for the transportation of passengers between concourse and landside building for each airport passenger building configuration:

a) Two-vehicle (100 pax/veh) dual-lane self-propelled automated people mover (APM) shuttle

b) Two-vehicle (100 pax/veh) dual-lane cable-driven automated people mover shuttle

c) Twelve shuttle buses (100 pax/veh)

d) Two parallel series of moving sidewalks per direction. It is assumed that passengers walk along the concourses as no moving sidewalks are provided.

Unlike moving sidewalks, APM technologies and buses provide batch service and are assumed to operate at constant headways for a particular configuration. It is also assumed that the APM has a constant station dwell time of 25 sec.

In a smaller airport, depending on the configuration, all systems with the exception of cable-driven APM provide about the same capacity of around 140 to 180 pax/min/direction(ppmpd). Because of the speed limitations of cable technology, its capacity is slightly lower by about 15%. All systems however, perform at reduced capacities (about 35% lower) for the midfield "+" configuration due to the significantly increased travel distance between concourse and landside building.

In a larger airport, with the increased traffic volumes, the following expanded systems are analyzed for all configurations except the Midfield "+" :

a) Three-vehicle pinched-loop self-propelled automated APM system

b) Three-vehicle dual-lane cable-driven automated APM shuttle system

c) Average of twenty shuttle buses depending on the configuration

Moving sidewalks are not considered for practical reasons given the distances involved. For expansion purposes, it is assumed that the APM systems provided for in Stage 1 (small airport) will be extended (along the same right-of-way) to serve the new midfield concourses in Stage 2 (larger airport). The initial self-propelled shuttle system will be modified and extended to a pinch-loop system, whilst the cable-driven shuttle system will be extended and will include an extra vehicle. The number of shuttle buses will be apportioned between the concourses to balance the queues and wait times. Given the geometrical layout of the Midfield "+" configuration, a new independent system exactly similar to that in Stage 1 is assumed to be provided to serve the new "+" concourse in Stage 2.

In a larger airport, both the self-propelled and bussing technology are capable of providing almost the same capacity of about 200ppmpd. The cable shuttle system, on the other hand (with the exception of the Midfield "+" concept), provides a far lower capacity (50% less) due to the increased distances, longer headway intervals and slower speed. Since independent shuttle APM systems have been provided in the Midfield "+" concept to serve each of the "+" concourses, the cable-driven system is still able to maintain a reasonably high total capacity of about 180ppmpd. Unlike the other three passenger building configurations, the cable system here does not have an intermediate stop(concourse) to contend with.

Appendix F gives a detailed comparison of the system characteristics for the different combinations of technology and configuration for both sizes of airports.

"Line-balancing"

The provision of capacity to the intermediate midfield concourse for all configurations (except the Midfield "+" concept) is an important consideration. The APM system does not provide equal service to both concourses. The capacity that is provided to the intermediate concourse is the total capacity of the system less the demand consumed at the first stop (in this case it is the second concourse for terminating traffic). For example, if a cable-driven shuttle system provides a total capacity of 90ppmpd and the demand at the second concourse is 75ppmpd, then the remaining capacity available to service the 1st concourse will be only 15ppmpd!

This is the crux of the "line-balancing" problem observed in all transportation systems. As the name suggests, the issue is therefore to provide adequate service capacity to all demand points, and to avoid situations where some points get little or no service. This kind of failure can easily happen in any system where many lines must be served by a common artery. Most of us have experienced the difficulties that arise when line-balancing has not been achieved e.g. unable to get on an elevator at rush hour from an intermediate floor of a high-rise office building because all the elevators are full with people who got on at higher floors.

Chapter 7.1 presents the results of our findings where it is found that the cable system is unable to provide the capacity demanded in particular to the intermediate stop for the three configurations, thus resulting in long queues.

<u>Door-to-door passenger Travel Time computation</u>

a) APM self-propelled and Cable : Walk time from gate to APM station + Wait time (include negligible loading time) + Transit time + Walk time through terminal.

Avg. transit time (sec) for self-propelled = 0.0215*x + 18.9;

Avg. transit time (sec) for cable-driven = 0.0229*x + 29.8, where x is the distance in feet

The above equations were derived from a regression analysis to provide the best fit to the data made available by well-known self-propelled and cable-driven APM suppliers [AEG 1995, OTIS 1995]. See Appendix G. These transit times are assumed to be constant for a particular combination of technology and configuration.

b) Bus : Walk time from gate to bus station + wait time (include loading time) + transit time (assume constant speed of 20-25km/h) + unloading time + vehicle maneuvering time + walk time through terminal;

c) Moving Sidewalk : Walk time from gate to center of concourse + wait time in queue + transit time (assume 30m/min) + intermittent walk time bet. moving sidewalks (assume 60m/min) + walk time through terminal.

The overall average travel time for a particular configuration is calculated as a weighted average of the average travel time contribution from each of the concourses; the overall maximum travel time is simply the largest value of the maximum travel time contribution of each concourse. Average and maximum travel times take into account the average and maximum wait times(in queues) and the walk times from the average and maximum distance gates respectively.

System Cost

Table 4.6 presents the cost estimates in 1993 US dollars based on recent survey information (see references in Chapter 3.2 under the description of the various systems). It also gives the discount rates and design life that are used to derive annualized system capital cost estimates, as well as the estimated proportion of total annual cost that is attributed to capital cost of system (remaining being the Operating/Maintenance cost of labor, materials etc.) [Lea & Elliot 1994, OTIS 1994, SATS 1995].

It is to be noted that the cost computations do not include civil construction cost. The Operating and Maintenance cost of buses constitutes a significant proportion of the total annual cost. This is due to the labor-intensive nature of the system. 30% more buses have been added to what is required to account for breakdowns and maintenance.

Table 4.6 : Cost Data for People Mover Technologies

Description	Self-Propelled	Cable-Driven	Bus	MS
Capital Cost ($)	4,680/km/pk.hr pax	4,270/km/pk.hr pax	330,000 each	9,000/m
Discount Rate (%)	10	10	10	10
Design Life (years)	20	20	15	10
Ann.Capital Cost as a % of Total Ann. Cost	77	77	20	90

Notation : MS = Moving Sidewalk; Ann. = Annual; pk. = peak

4.5 Baggage Transport Approach and Assumptions

The following technologies are compared in both airport sizes for all airport passenger building configurations for the transportation of baggage between the landside building and aircraft and vice versa :

a) Telecar (automated multi-bag cart system)

b) DCV (automated single-bag destination coded vehicle system)

c) Tug and Cart

The tug and cart system is also used under the following circumstances:

- to supplement the telecar for transporting originating bags from the telecar unload stations (assumed to be centrally located within the airside concourses) to the aircraft. The reverse process also holds for the terminating bags.
- for the DCV system, tug and carts are assumed to be used to deliver the bags from the gate make-up to the aircraft and vice versa.
- to transport bags to the gates along the linear and pier concourses which are attached to the landside building under the hybrid concepts, even though the telecar and DCV are used as the main form of transport to the midfield concourses.

The flowcharts in Figures 4.6 and 4.7 indicate the sequence of activities for originating and terminating bags associated with the computation of the door-to-door bag travel time for the different technologies. The originating process represent the period required to process the <u>last</u> bag for a given flight from check-in to the average and maximum distance gates. The last bag is considered to be the most critical as it will determine the flight close-out time of an airport. Acceptable standards at most major airports today is about 15 mins.

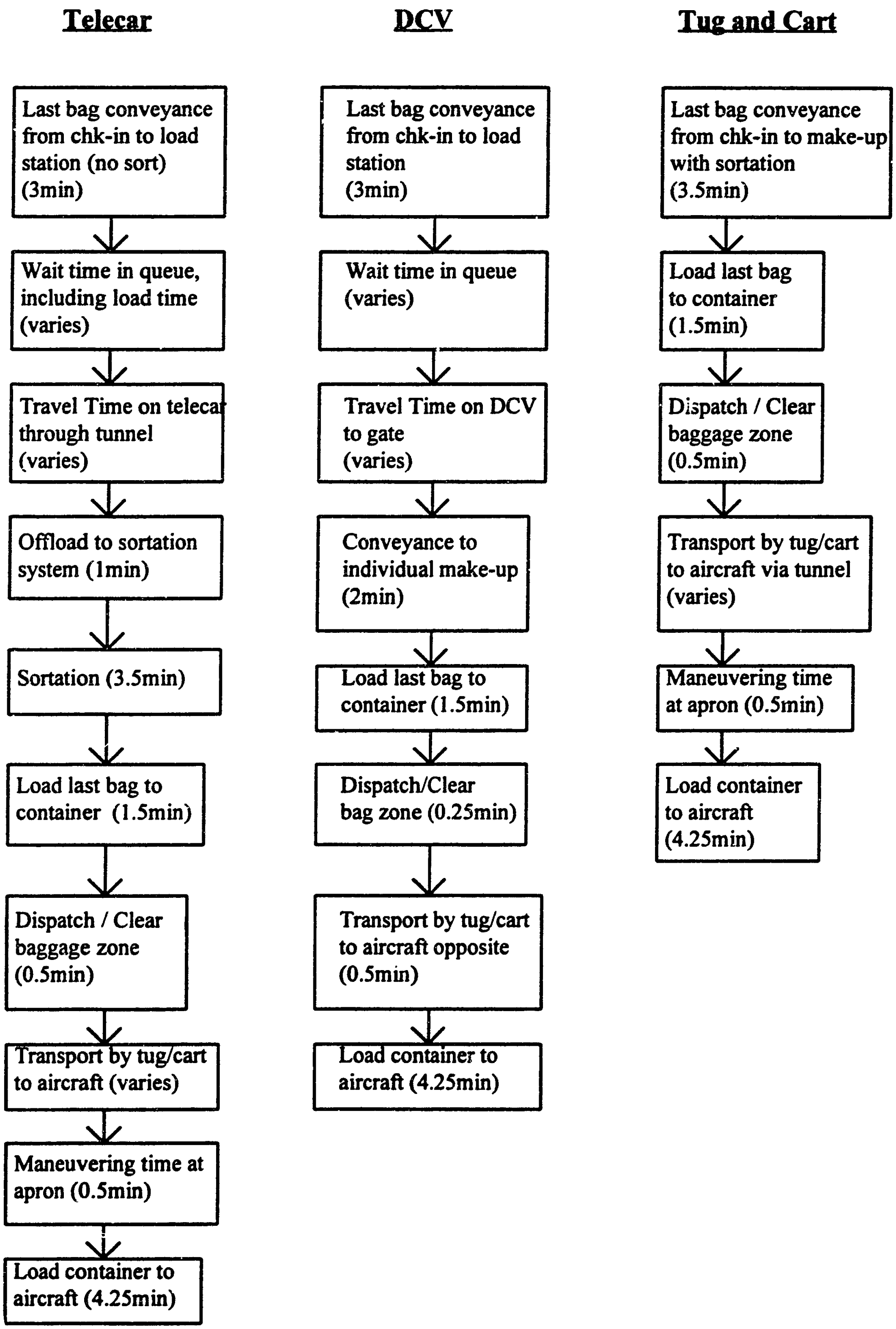


Figure 4.6 : Flow of Originating Baggage

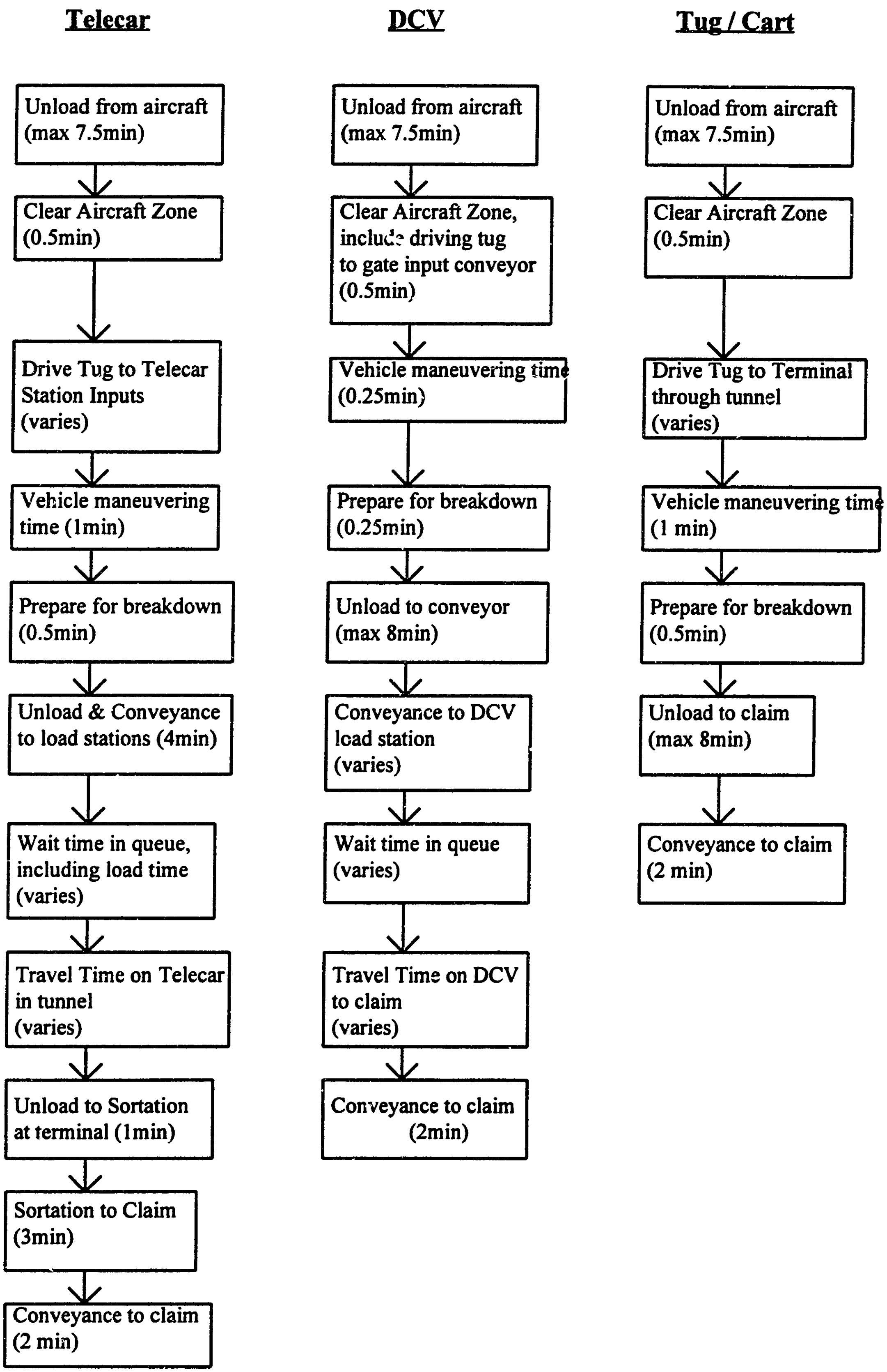


Figure 4.7 : Flow of Terminating Baggage

Telecar

For a small airport, dual-tracks (per direction) with eight stations(loading and unloading) at each end (i.e. 4 per line) are assumed to be provided for point-to-point transport between the landside building and the midfield concourse. For larger airports, a similar independent system with the same number of lines and stations are also assumed to be provided to serve the second midfield concourse along the same right-of-way.

Dual lines (per direction) are provided as the minimum needed to deal with the possibility of system failure to one line. Together with the 8 loading stations, it is able to provide an equivalent "theoretical/calculated" capacity to that of the DCV system (described below) of around 70 to 80 bags/min per direction per concourse. This will therefore provide a fair and equal basis for comparing the different automated technologies.

As the telecar is assumed to provide only general point-to-point transport, an independent sortation process of about 3.5min is assumed to take place at the airside concourse(s) to sort originating bags to the respective flight make-up devices before final delivery to the aircraft by tug and cart. It is assumed that adequate sortation capacity is provided to accommodate the loads without any delay.

The process repeats itself for terminating bags where bags are brought from the aircraft to the telecar load station inputs, unloaded/conveyed to the load stations (assume bags uniformly distributed to all load stations to utilize the full capacity), transported back to the main terminal, and finally sorted via an independent sortation activity to the respective baggage claim device.

"Practical" versus "Calculated" capacity

Facilities that process variable flows of traffic behave in special ways that need to be understood. They all tend to create queues and cause delays when the traffic is heavy [de Neufville 1976]. Furthermore the situation worsens as the traffic comes nearer to the calculated capacity where the system then becomes very unstable. In recognition of this fact, designers should not plan to have systems operate near capacity but allow for a margin of safety.

In addition to the above, the calculated capacity is based on the assumption that flows proceed smoothly and mesh together without interference or wasted space or motion. This assumes that everything will fit closely together. But in practice, nothing of this sort happens especially in a system like the telecar and DCV where carts are spaced at such close intervals, and therefore the effects of mutual interference cannot be discounted. Mutual interference prevents the system from delivering all it theoretically could.

The other consideration is the issue of "line-balancing". In a complex system like the DCV and even the telecar, it is crucial to control the capacity of the system so that all lines of flow are balanced. The issue is to provide equally good service to all lines. For example in a DCV system, sufficient empty carts must be provided to each of the conveyor lines that feed bags onto the system of carts. It is important to avoid situations where some lines get little or no service; this can easily happen in a system like the DCV where so many lines must be served by a common artery. Solving this "car-starving" problem, as experienced at the new Denver International Airport can be extremely difficult, especially for complicated systems with a high number of lines of access.

Recognizing the above issues, it is assumed that the actual practical/achievable capacity is only about half of the ideal calculated/theoretical capacity. Hence in order for the system to function at the calculated capacity, a doubling in the investment of the system (of what has been assumed above) is required. For example, four tracks (instead of two) per direction and sixteen loading stations (instead of eight) at each end are required between the landside building and a midfield concourse.

The queuing model (described in Chapter 5) computes the waiting times in queues (over a range of possible loads) that are assumed to occur at the load stations when demand exceeds capacity for both originating and terminating bags. The model also determines the overall average and maximum door-to-door travel times based on the entire sequence of activities.

DCV

The DCV system is assumed to be arranged as a series of two independent loop systems (from the landside passenger building) to serve each concourse i.e. one for each half of a midfield linear concourse or each arm of an "X / +". Loads are assumed to be equally distributed between the two loop systems. Two independent loop systems per concourse are assumed so as to provide a back-up for each other in the event of system failure and also to provide the "calculated" capacity equivalent to the telecar system.

However, recognizing the mutual interference effects on capacity and the line-balancing problems as explained above, it is assumed that the investment in the system will have to be doubled in order for the DCV system to function at the calculated capacity. Therefore, four independent loop systems (instead of two) is needed to serve each concourse from the landside terminal and double the number of carts are required.

Originating bags are assumed to be automatically tracked from check-in by sophisticated controls, conveyed to the load stations and individually delivered/sorted by the DCV via the shortest route to the respective make-up device at the gate, for final delivery to the aircraft by tug and cart. Terminating bags are assumed to be delivered by tug/cart to the gate inputs, unloaded at the load stations, and individually delivered/sorted by the DCV back to the respective claim device at the terminal.

The deterministic cumulative queuing model predicts that queues build up when total demand over the short term exceeds total capacity. Like the telecar system, the model computes the average and maximum door-to-door travel times to the average and maximum distance gates (based on the entire sequence of activities) for each concourse, and derives the overall maximum and average (weighted by total aircraft gate capacity at the concourse) for the configuration. These times take into account the average and maximum wait times in queue.

Both the telecar and DCV are assumed to travel at an average speed of 9 km/hr for the first and last 50m to allow for acceleration and deceleration, and 31 km/hr over the rest of the journey [WH Pacific 1995].

Tug and Cart

Originating bags are assumed to be conveyed from check-in and either manually or automatically sorted to make-up devices within the landside building, before being loaded onto containers for delivery to the aircraft. It is assumed that adequate sortation capacity is provided to accommodate the loads without delay; approximately 3.5 min is allocated for this activity. Terminating bags are conveyed directly from the aircraft to the respective claim device. One man is assumed to be assigned to unload every two containers at claim device at the rate of 10 bags/min.

Unloading activities from aircraft are assumed to comprise of opening of a/c doors, positioning of loader and dollies and unloading of containers. These are assumed to take about 7.5min. On the other hand, loading of the last container to an aircraft for originating bags is estimated to take 4.25min. It involves the loading of container, pushing back of loader and closing of aircraft doors [WH Pacific 1995].

An average travel speed of 12km/h is assumed for movement through the tunnel, whilst a reduced speed of 6 km/h is assumed along apron roadways given the slower driving conditions along the often congested aprons.

Assuming a 30m headway between successive tugs (20m for four-container length + 10m spacing), the capacity of a single-lane per direction tunnel is calculated to be 6.7 tugs/min or 1067 bags/min. This is above the peak directional demand of 200 bags/min for a 30 to 40million passenger per annum larger size airport, and therefore no congestion nor reduction in travel times are assumed to occur in the tunnel. The effects of other apron / ground servicing vehicles in the shared tunnel is assumed to be negligible in comparison to the volume of the tug and carts. Hence, no capacity constraints are observed for the tunnel.

System Cost

Table 4.7 shows the cost estimates in 1993 US dollars based on a recent survey of cost data (see references in Chapter 3.3 under the description of the various systems). It also gives the discount rates and design life assumed for the derivation of annualized capital cost, as well as the estimated percentage of total annual cost attributed to capital cost of system [BNP 1990, 1994a].

The tug and cart is an extremely labor-intensive operation, where practically all of the annual cost is in the form of wages for the drivers, ground handlers, etc. Although automated, the telecar system is still relatively labor-intensive. Most of the operating and maintenance costs is also in the form of wages for the drivers and handlers that are needed to manually load/offload bags from the system, and to transport the bags to/from

Table 4.7 : Cost Data for Baggage Transport Technologies

Description	Telecar	DCV	Tug and Cart
Capital Cost ($)	10,000 / m track (including vehicles)	10,000 / m track 10,000 / vehicle	29,000 / tug 3,500 / cart
Discount Rate (%)	10	10	10
Design Life (years)	20	20	5
Ann. Capital Cost as a percentage of Total Ann. Cost (%)	20	30	2

the aircraft by tug/carts. The DCV system requires a slightly lesser labor content. However, like the telecar system, labor is still needed to transport bags by tug/cart from each of the gates to the aircraft.

It is to be noted that the cost analysis does not take into consideration the civil construction cost. The following are further assumptions made with regards to cost computations :

a) Telecar : In addition to the length of the tunnel, an extra 20% is added to account for the additional tracks at the stations, maintenance areas and bypasses.

b) DCV : An extra 20% of guideways is added to account for additional tracks at stations, bypasses etc. Double the number of vehicles required during the peak period is assumed to be provided to cater for breakdowns, maintenance and in recognition of the complexity of the system as explained above.

c) Tug / Cart : The number of tug/carts required is calculated on the basis of satisfying the peak period volume. An additional 30% more is provided for breakdowns and maintenance.

CHAPTER 5 - QUEUING ANALYSIS MODEL

5.1 Fluid Approximation to Queuing Analysis

The congestion that occurs in airports is due to transients, always undergoing some kind of dynamic change. The queuing processes rarely attain steady state [Odoni and de Neufville 1992]. Rather they build up along with the peaks of traffic and then dissipate. In this thesis, we examine the process where large queues form over a short period of time caused by the initial surge of passengers/bags upon the arrival of a flight, for example. In such cases, the average arrival rate will be greater than the average service rate. The textbook mathematical approaches based on classical, steady-state queuing theory (e.g. Lee 1966) for calculating queues are thus generally not applicable for airport passenger buildings.

The appropriate method for dealing with transients is the deterministic graphical approach developed by Newell (1971). It has been used by Horonjeff and Paullin (1969) for the sizing of departure lounges in airports, and ticket counters by de Neufville and Grillot (1982). Newell presented various approximations of queuing analysis based on the principles of fluid dynamics. These are most useful when rather large queues form. This approach presumes that the pattern of loads is known; it simply combines representative plots on cumulative arrivals with plots of cumulative service/departures, as shown in Figure 5.1 (explained below), to estimate directly from the graph all necessary results e.g. queues and delays.

Newell defined the functions A(t) and D(t) to represent the cumulative number of arrivals and departures/served by time t, at a queuing system. He also defined the arrival ("flow in") and departure ("flow out") rates as $\lambda(t)$ and $\mu(t)$, which are simply the first derivatives of A(t) and D(t) respectively. From this, one can derive simple relationships to determine the number of items present in the system at any time t. A(t) and D(t) can be expressed as :

$$A(t) = \int_0^t \lambda(t).dt \tag{5.1}$$

and

$$D(t) = \min \left[\int_0^t \mu(t).dt \, , A(t) \right] \tag{5.2}$$

D(t) is the minimum of the two components as there cannot be more departures than arrivals into a system (unless there are queues present in the system at t = 0).

Newell further defines the queue or the number of items present in the system at time t, as

$$Q(t) = A(t) - D(t) + Q(0) \tag{5.3}$$

For our purposes, Q(t) represents the number of passengers or bags in the system and waiting to be served at time t. We are particularly interested in the behavior of Q(t) throughout the peak period and the identification of the average and maximum Q(t) over the time interval under consideration.

The above relationships can be represented graphically in the form of cumulative arrival and departure diagrams. These indicate how many passengers or bags have accumulated up to some point in time from an initial start time and the total number of passengers or bags that have arrived or departed up to that point in time. They are important because they provide many of the performance measures of interest in one simple picture (See Figure 5.1).

Quantity in queue or queue length, Q(t) at any time t is determined by the vertical distance between the curves. The maximum value, $Q^*(t)$, represents the maximum queue over the entire time period. On the other hand, the time spent in queue for the nth customer or the waiting time/delay, w(n), is the horizontal distance between A(t) and D(t)

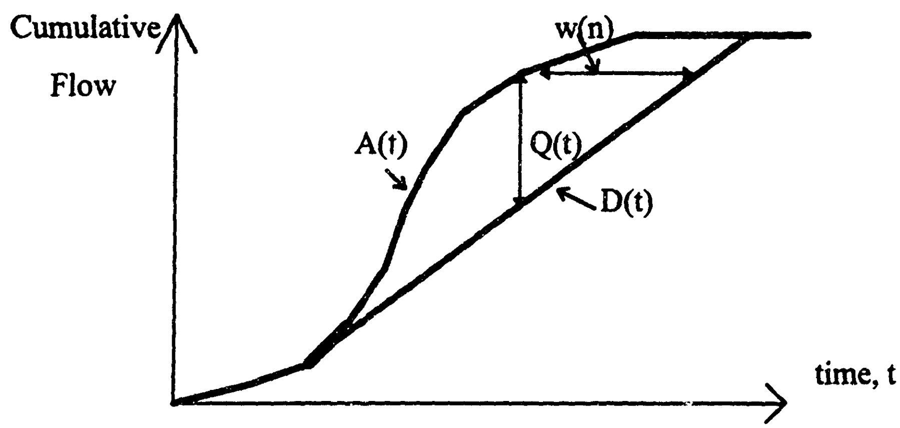


Figure 5.1 : Cumulative Arrival and Departure Diagrams

at the height n. The maximum value $w^*(n)$ is the maximum wait time in queue for a particular customer over the entire period.

The average wait time per customer equals the total wait time or the area bounded between A(t) and D(t) divided by the total number of customers, N served [Newell 1971, Randolph 1991]. It is usually computed over a period of time that begins and ends with no customers in the system. Hence

$$\text{Average Wait time in Queue, } \bar{w} = \sum_{n=1}^{N} w(n) \;/\; N \tag{5.4}$$

The average queue length is the average number of customers in queue over some time interval, usually. Suppose a = start time, and b = end time of interval, then

$$\text{Average Queue length, } \bar{Q} = \frac{\text{total wait time}}{\text{time interval beginning and ending with no customers in system}}$$

$$= \sum_{n=1}^{N} w(n) \;/\; (b-a) \tag{5.5}$$

The queue discipline by which customers are served is assumed to be on a first-come-first-serve basis (FCFS), where customers are served in the order of their arrival.

Figure 5.1 illustrates a situation whereby both the arrival and departure process are relatively steady. There are however many situations where it is not, for example, the arrivals are fairly steady but the service is irregular or "stepped". In this thesis, we examine the process where passengers arrive during the surge period at a relatively steady rate to board an automated people mover train that provides batch service at constant headways, for example. Passengers deboard and board the train for the period of time that the train is programmed to dwell at the station, before it leaves. "New" passengers arrive and queue until the next train arrives. Hence the queue grows and does not shrink until the arrival of the next train.

5.2 Computer Model

Based on the principles of fluid approximation for analyzing queues as described in the preceding section, a flexible computer-based "EXCEL spreadsheet" model has been developed to compute the various measures of performance of any combination of technology and passenger building configuration over a range of loading situations. It allows the design team to ask "what if" questions readily.

Slight modifications are made to the model to account for the different operating characteristics of the various technologies for both passengers and bags. For instance, moving sidewalks provide continuous constant service instead of batch service characteristic of automated people movers. The general principles, with the exception of the tug/cart technology (does not make use of the model as no queuing other than the loading/offloading of bags is assumed to occur), are similar.

The results are calculated at every 0.5min interval to achieve reasonable approximations. It should be noted that given the uncertainty in traffic to begin with, it is meaningless to obtain an accurate assessment of the performance of a given combination in absolute terms. The information that is truly useful is the relative performance of the different combinations, and their ability to meet the range of possible loads. The main outputs of the model are :

a) Waiting time in queue

b) Length of queue

c) Overall door-to-door travel time, which includes the walk time, wait time, transit time, loading/unloading time, sortation time etc. depending on the technology examined (see discussion in Chapter 4.4 and 4.5)

For each of the above outputs, the model calculates both the average and maximum values.

The general algorithm of the model for any combination of technology and airport passenger building configuration is as follows :

Steps :

1. Input the passenger / baggage demand rate, the calculated service rate of the technology, the load distribution and the travel distances of the configuration. The distribution of loads amongst the concourses and the average / maximum travel distances are determined from the geometrical construction, estimates of walk distances and the other assumptions discussed in Chapter 4.

2. Based on a comparison of the demand and service rates, establish the actual or observed service rate.

3. Derive the cumulative demand and service curves. Given the batch service nature of the technologies examined with the exception of moving sidewalks, determine the actual / observed cumulative service curve based on the assumed or computed headways (assumed to be constant).

4. From the derived cumulative curves, calculate the queue, cumulative wait time at any point in time and the wait time of each passenger / bag served. The queue length and wait times are simply the vertical and horizontal distances between the two cumulative curves.

5. Calculate the average and maximum wait time in queue, queue length using the results obtained in step 4 and also equations 5.4 and 5.5.

6. Determine the average and maximum overall door-to-door travel time for passengers / bags given the above results.

Appendix H contains sample calculations of the performance of a self-propelled pinched-loop APM system for a hybrid centralized linear with midfield linear 56-gate configuration.

CHAPTER 6 - DEALING WITH GROWTH

This chapter presents the methodology for dealing with the question of growth in the longer term. Specifically, one may ask, what is the best and most flexible / expandable strategy to adopt in terms of the optimal combination of technology and configuration, over the longer term given the massive uncertainty about future loads. A particular combination may perform exceptionally well initially but miserably in the future when conditions change. It is therefore advisable to select a technology that will perform reasonably well over its entire useful life. The chosen strategy should remain "robust" by exhibiting consistent performance over a variety of changing conditions. The inability to predict future conditions accurately makes the selection of a robust system critical to the long term success of an airport.

6.1 **Methodology**

Uncertainty, in particular, makes decision making difficult. It raises questions on how choices should be evaluated when the consequences are uncertain, what alternatives provide more flexibility in responding to uncertainty.

These questions can best be answered through the use of a methodology known as Decision Analysis [de Neufville 1990]. It provides a logical framework for decision making based on what you know (uncertainties), what you can do (alternatives), and what you prefer (values). A decision analysis computer-based model is used for this purpose. It uses decision trees to describe the possible alternatives for each decision and the possible states for each uncertain(chance) event, thus fully describing all the possible future scenarios, together with the values/outcomes of all possible alternative scenarios. This process provides a logical and systematic process for enumerating all possibilities in the form of competing alternatives, and uncertain consequences, in arriving at the overall "best" decision on the average.

The optimal decision maximizes the expectation (probability weighted sum) of the values. Sensitivity analysis can be carried out to examine changes to the decision making process when an uncertain variable is set to its extreme points while holding all other variables constant and to establish confidence in the results.

6.2 **Structure of decision**

Figure 6.1 shows the structure of the decision tree used for the analysis. It is both a graphical representation of the decisions, uncertainties, and values in a problem, and a framework for numerical evaluation. The nodes in the decision tree display all the possible combinations of decisions and uncertain states. There are two kinds: decision nodes(D) and chance nodes(C). Each has branches that represent the possible states.

The decision node branches represent alternative choices; in this case, the passenger building configuration (first level decision node) and the choice of technology (second level decision node). The chance node branches represent possible states for the uncertain event; traffic growth (to a larger airport i.e. Stage 2) or no traffic growth beyond a smaller airport (remain at stage 1). Chance node branches have associated probabilities of growth / no growth. A value(outcome) is attached to the ends of the chance branches to represent the performance of that particular combination of configuration and technology for a certain situation (smaller or larger airport).

The optimal expected value decision is determined using these values and the probabilities. Sensitivity analysis is carried out to examine changes in the decisions over the following range of probabilities of traffic growth : 0% (no possibility for growth due to site constraints), 50% and 90%. Chapter 7 uses this methodology for establishing the best combination of technology and passenger building configuration over time.

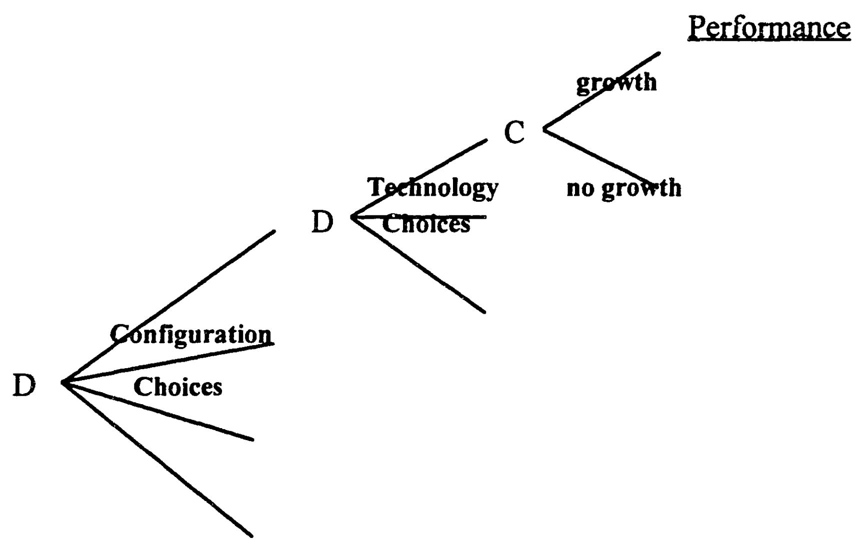


Figure 6.1 : Decision Tree Structure

CHAPTER 7 - PRESENTATION OF RESULTS

7.1 Passengers

7.1.1 Best combination of technology and configuration for each size of airport

For each airport passenger building configuration, an analysis is carried out using the queuing model described in Chapter 5 to determine the performance of the different people mover systems over a range of loading conditions for each of the two airport sizes, with respect to the following performance criteria : average and maximum queue, travel time, walk distance, and system cost. "Performance Profiles" are plotted to demonstrate the relative performance of the APM self-propelled, APM cable, Bus and Moving Sidewalk. Figures 7.1 and 7.2 show typical results for a Smaller Airport (28-gate) Midfield Linear configuration in terms of average queue and maximum travel time performance of the different systems.

The results are then averaged over the range of loads envisaged for each size of airport as identified in Table 4.5, to represent the performance of each system. For example, in the case of a smaller airport, we take the average over the range of 50 to 75 pax/min, but 100 to 150 pax/min for a larger airport to reflect the higher traffic volumes. It is to be noted that the analysis focuses on the terminating passengers as this is the more critical scenario where systems are subjected to higher surges of peak loads. Table 7.1 tabulates the final results for all possible combinations of technology and configuration.

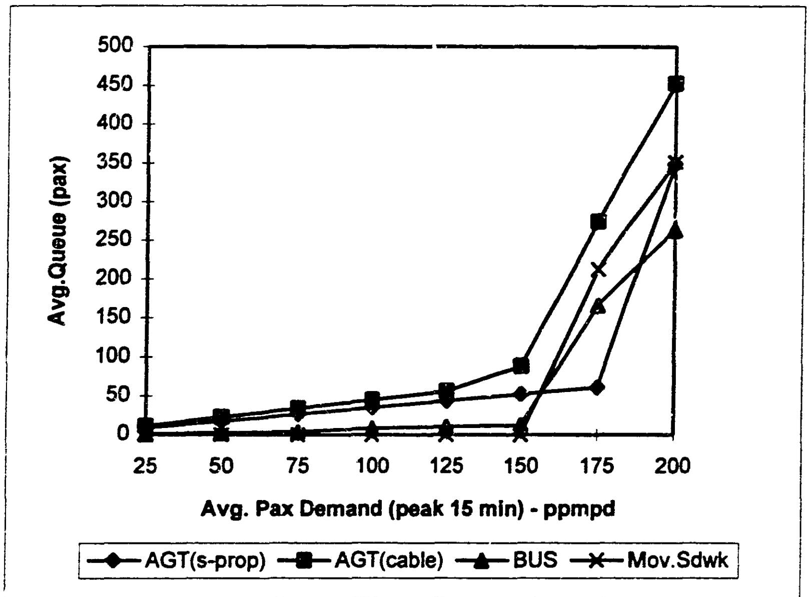


Figure 7.1 : Smaller Airport - Midfield Linear Configuration
Average Queue Comparison for People Mover Technologies

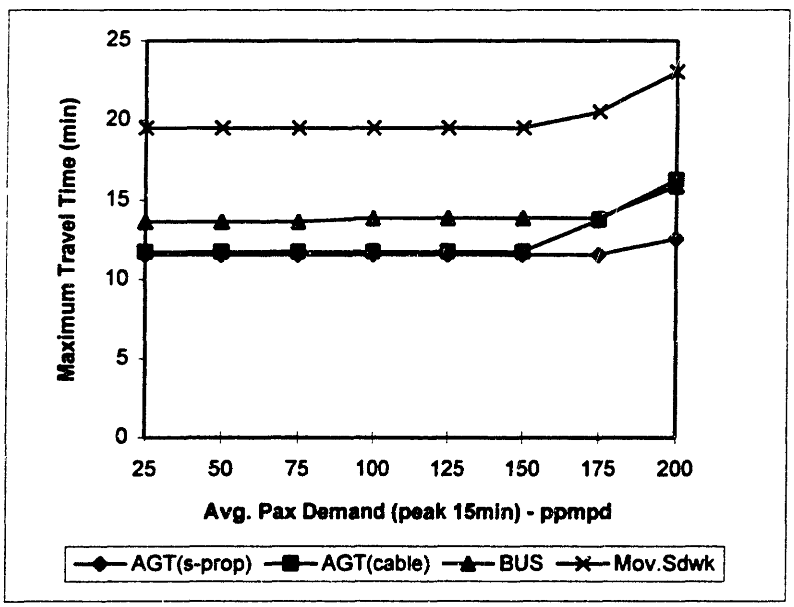


Figure 7.2 : Smaller Airport - Midfield Linear Configuration
Maximum Travel Time Comparison for People Mover Technologies

TABLE 7.1 : Performance of People Mover Technologies for various Passenger Building Configurations

Smaller Airport : 28 gates - 15 to 20 million pax/yr
Peak 15 min demand volume = 50 to 75 pax/min

Performance criteria	Midfield Linear				Midfield "+"				Hybrid Ctrl./Mid.Linear				Hybrid Ctrl.Pier/Mid."X"			
	SP	CB	BUS	MS	SP	CB	BUS	MS	SP	CB	BUS	MS	SP	CB	BUS	MS
Queue (pax) - Avg.	22	29	4	0	46	56	13	0	16	20	4	0	19	25	5	0
- Max.	63	63	32	0	94	125	32	0	40	40	20	0	44	62	21	0
Travel Time (min) - Avg.	6.5	6.8	8.8	15.1	8.0	8.5	11.0	38.0	5.5	5.7	7.0	12.7	6.8	7.0	8.4	17.5
- Max.	11.6	11.8	13.7	19.5	10.3	11.1	12.8	39.5	9.5	9.7	11.7	20.3	8.7	9.4	11.1	24.4
Walk Distance (m) - Avg.	326	326	326	426	342	342	342	518	283	283	283	355	347	347	347	417
- Max.	561	561	561	661	405	405	405	581	432	432	432	545	439	439	439	475
System Cost / Pax (cents)	38	30	25	3	68	55	25	11	44	34	25	4	52	42	25	6

Larger Airport : 56 gates - 30 to 40 million pax/yr
Peak 15 min demand volume = 100 to 150 pax / min

Performance criteria	Midfield Linear			Midfield "+"			Hybrid Ctrl./Mid.Linear			Hybrid Ctrl.Pier/Mid."X"		
	SP	CB	BUS	SP	CB	BUS	SP	CB	BUS	SP	CB	BUS
Queue (pax) - Avg.	31	138	16	46	56	15	27	89	14	41	110	14
- Max.	63	395	63	94	125	31	63	217	40	63	316	41
Travel Time (min) - Avg.	7.3	9.9	9.9	8.0	8.5	11.6	7.0	8.4	9.3	7.9	10.2	10.6
- Max.	12.8	17.5	15.2	10.3	11.1	13.4	13.3	16.1	15.9	11.1	17.3	14.3
Walk Distance (m) - Avg.	326	326	326	342	342	342	316	316	316	357	357	357
- Max.	561	561	561	405	405	405	585	585	585	439	439	439
System Cost / Pax (cents)	49	23	15	133	106	25	55	26	20	75	31	20

Notation : SP - Self-Propelled APM; CB - Cable-Driven APM; MS - Moving Sidewalk; Avg. - Average; Max. - Maximum; Ctrl. - Centralized; Mid. - Midfield

Smaller Airport (28-gate)

Both the self-propelled and cable systems provide essentially the same level of service in terms of queue lengths (see Figure 7.3) and travel times (see Figure 7.4), with the average and maximum travel times not exceeding 9 and 12 min respectively. The self-propelled system has a slight, probably insignificant edge. Hence a cable-driven system is able to provide almost equal performance over short distances despite its slower speed.

The travel time of bussing is not as good, taking about 20% longer because of the extra time needed for loading/unloading, and maneuvering of the vehicles in/out of the stations. However, given the more frequent headways, queues are found to be less than the automated self-propelled and cable systems. Moving Sidewalks, on the other hand, perform miserably due to their low speeds and the intermittent walking required between the moving sidewalks (see Figures 7.4 and 7.5). Depending on the configuration, moving sidewalks could take on the average 15 min (midfield linear concept) to 38 min (midfield "+") of travel time; the "+" being significantly higher due to its greater distance from the landside building. Queues however, do not form for moving sidewalks as they are capable of delivering the "continuous" capacity to meet the envisaged demand.

From the system cost perspective, the less attractive and less expensive bussing and moving sidewalk technologies are favored; with the self-propelled being the most expensive at 38 cents/pax (midfield linear concept) compared to 3 cents/pax for moving sidewalks (about 13 times!). See Figure 7.6. Taking level of service into consideration, it appears that the cable-driven system or bussing are the more cost-effective alternatives for a smaller airport given the relatively short distances and the good performance of these systems over such distances.

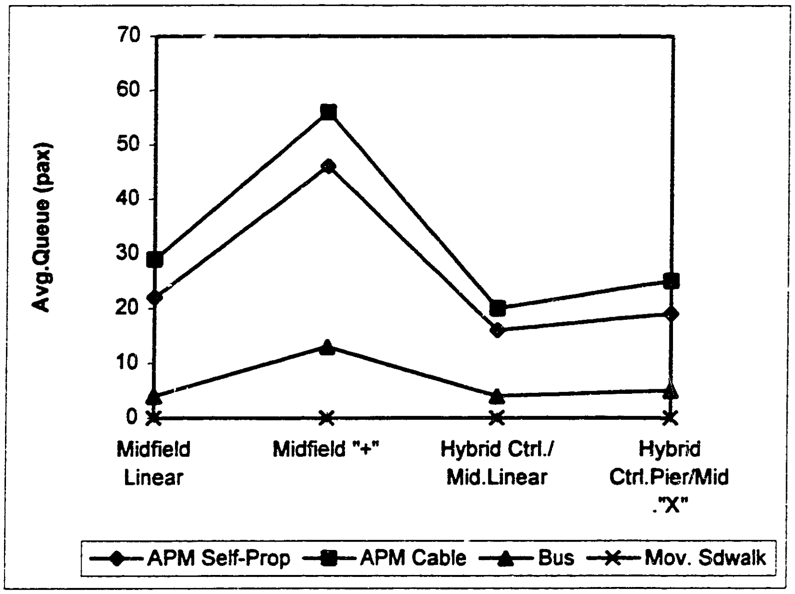


Figure 7.3 : Smaller Airport - Average Queue Comparison of Passenger Transport Technologies for Different Passenger Building Configurations

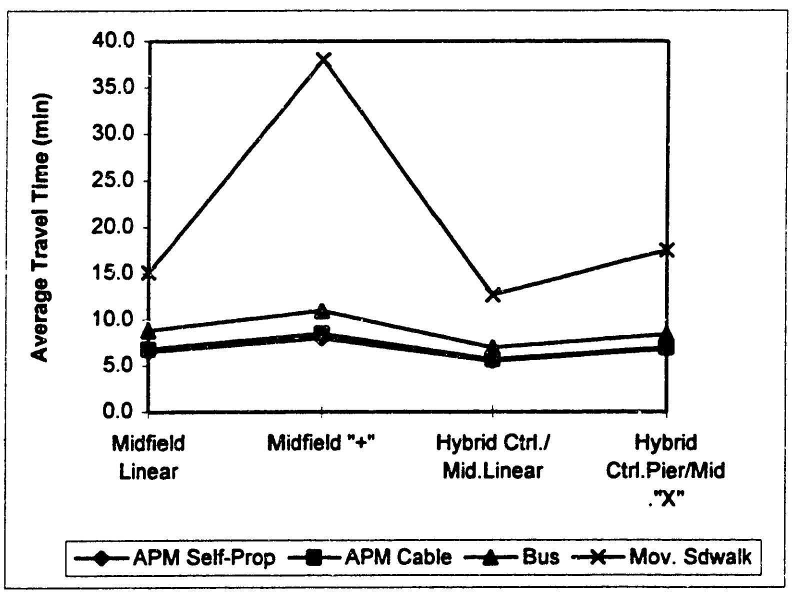


Figure 7.4 : Smaller Airport - Average Travel Time Comparison of Passenger Transport Technologies for Different Passenger Building Configurations

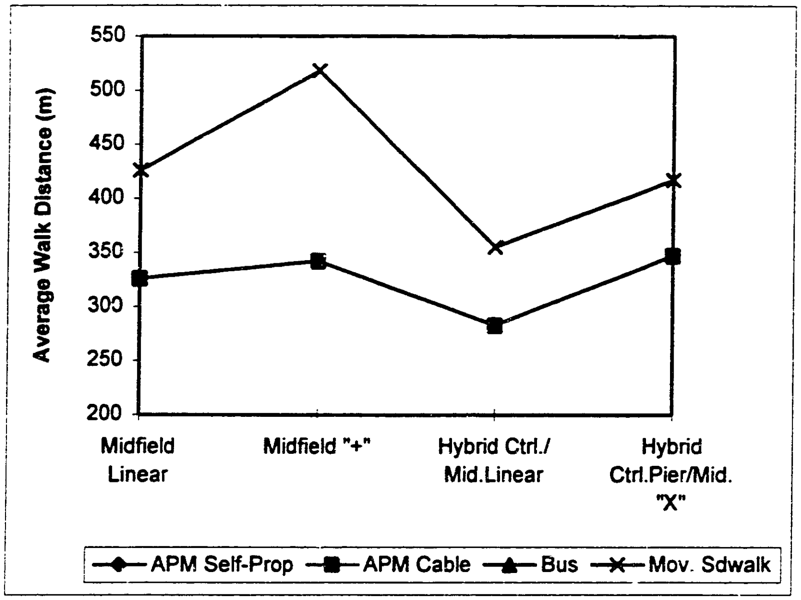


Figure 7.5 : Smaller Airport - Average Walk Distance Comparison of Passenger Transport Technologies for Different Passenger Building Configurations

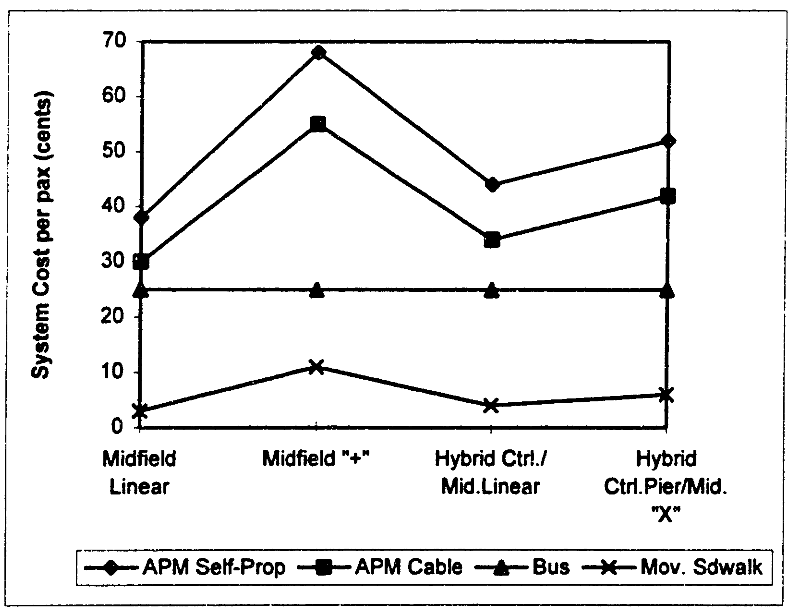


Figure 7.6 : Smaller Airport - System Cost Comparison of Passenger Transport Technologies for Different Passenger Building Configurations

As for the best combination of technology and passenger building configuration, the results show that either of the two systems i.e. cable-driven APM or bussing, together with the hybrid centralized linear with midfield linear concept would give reasonably good overall performance. From the travel time perspective, the cable performs better, whilst bussing gives better performance in reducing queues. But since passengers are known to be more time sensitive, coupled with the fact that the level of comfort on buses is usually low (especially when operating at capacity), the optimal preferred combination would thus be the cable-driven APM plus the hybrid linear configuration.

The midfield "+" configuration, with any combination of technology generally does not perform as well as the others (for a small airport). Because of the increased distance from the landside building (thus longer headways) and the higher average walk distance for passengers, both the queues and average travel time are longer. It performs well with the self-propelled and cable-driven systems only where maximum walk distance and travel time criteria are concerned. In such a case, one may choose to select the more cost-effective cable-driven system as it provides almost equally good performance as the self-propelled over this distance.

Larger Airport (56-gate)

For larger airports (with the exception of the midfield "+"), with the longer distances, the expanded self-propelled pinch-loop system outperforms both the bussing and the cable-driven shuttle systems in terms of travel time (its maximum 14min). The travel time on the cable system could take between 30 to 40% longer (see Figures 7.7 and 7.8), with queues 3 to 5 times as long as the self-propelled system (see Figure 7.9). Therefore the lower frequency, longer headways of around 3min, and thus low capacity cable shuttle system performs poorly especially under higher loads, giving rise to longer queues and wait times and thus a low level of service. The self-propelled

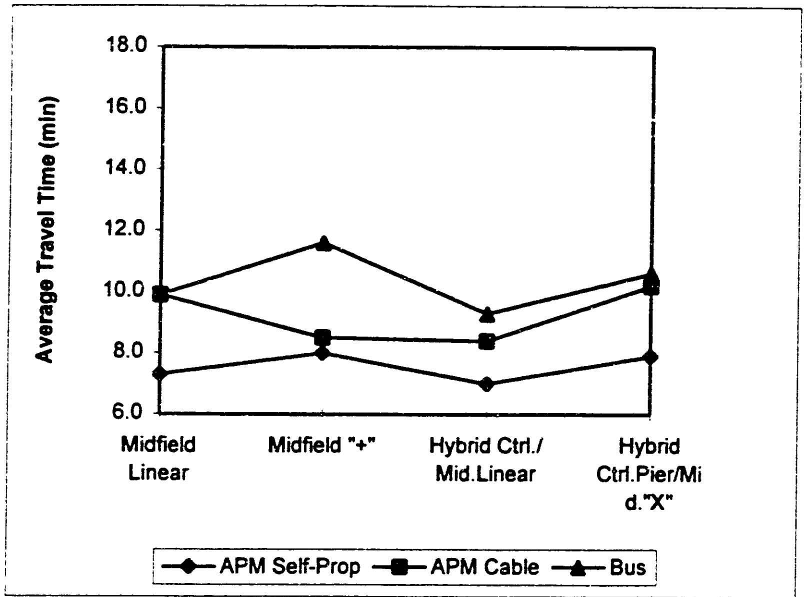


Figure 7.7 : Larger Airport - Average Travel Time Comparison of Passenger Transport Technologies for Different Passenger Building Configurations

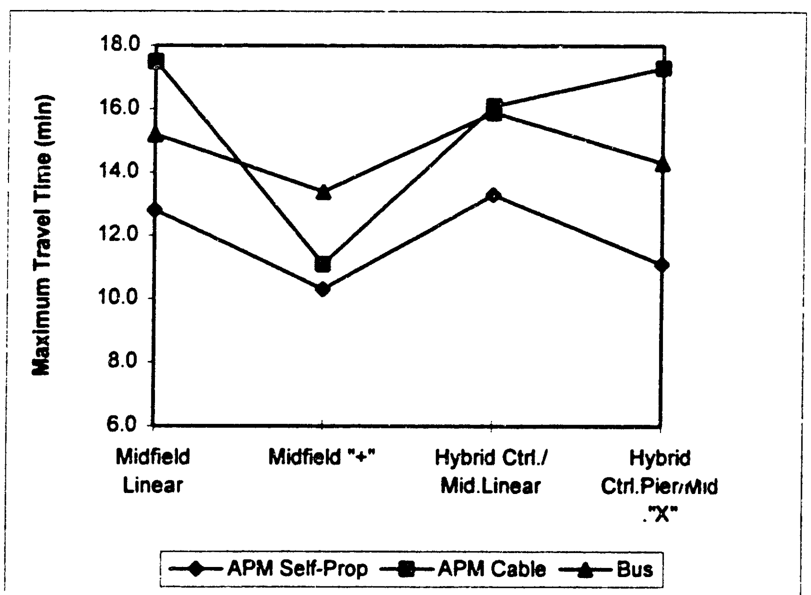


Figure 7.8 : Larger Airport - Maximum Travel Time Comparison of Passenger Transport Technologies for Different Passenger Building Configurations

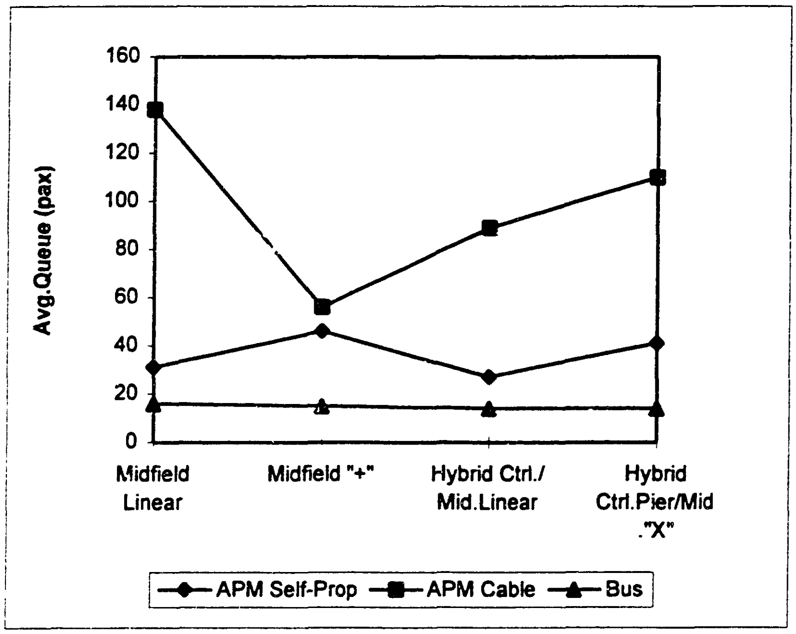


Figure 7.9 : Larger Airport - Average Queue Comparison of Passenger Transport Technologies for Different Passenger Building Configurations

pinched-loop system, on the other hand, can operate at higher frequencies and shorter headway intervals, as low as 90 sec assumed for this study. It is therefore a high capacity, high performance system. Bussing, although taking 25 to 35% longer than the self-propelled APM system due to its relatively slower speed, has the advantage of reducing queue lengths because of the more frequent headways. Although the most expensive system, the self-propelled APM appears to be a worthwhile investment in order to maintain at least a reasonable or even a high level of service. Bussing could also be considered as a viable cost-effective alternative, although normally not as attractive to passengers in terms of comfort.

According to the assumptions in Chapter 4.4, it is assumed that independent similar shuttle systems are provided to serve both the "+"s in the Midfield "+" configuration, as opposed to a modification/extension of the initial system assumed for the other three configurations. Thus it is found that in particular, the total capacity of the two independent (2-veh) cable shuttle systems for the midfield "+" configuration is higher than the capacity of the single extended (3-veh) cable shuttle system provided for the other three configurations (which all have an intermediate concourse stop). This explains why the cable system performs better in a midfield "+" configuration as compared to its performance with the other configurations (see Figures 7.7, 7.8 and 7.9). In fact, it performs almost as well as the self-propelled shuttle system (for this "+" configuration) because the distance from the landside building still allows the cable to perform reasonably well.

As for the best combination of technology and passenger building configuration, it appears that either the self-propelled APM system or bussing again combines reasonably well with the hybrid centralized linear and midfield linear concept; the former giving better average travel times and the latter less queues. Given that passengers are usually sensitive to travel time and do not "enjoy" riding in a bus, the self-propelled APM plus hybrid linear combination would therefore be preferred. However, maximum travel time performance of this combination is not as attractive due to the longer maximum walk distance that passengers would have to traverse along the linear concourses. In any case, with intelligent gate assignment where larger aircraft are expected to be assigned to gates closer to the center of the concourse, the average walk distance and travel time for a greater proportion of passengers is minimized. This combination should therefore provide a reasonably high level of service on the whole for most of the passengers.

If one is concerned only with setting the maximum travel times and walk distances as the most important crite ia to satisfy a very small proportion of passengers, then the cable-driven APM (more cost-effective than self-propelled with almost similar performance) plus the midfield "+" configuration would be desirable.

7.1.2 Best combination of technology and configuration over time

To determine the best combination over the long term, three scenarios of future traffic growth are examined as follows:

a) No possibility for growth beyond Stage 1 (smaller airport) e.g. due to site constraints
b) 50% chance of possible traffic growth to Stage 2 (larger airport)
c) High 90% chance for growth i.e. high certainty that an expanded passenger building complex will be required to handle double the volume in Stage 1.

Using the methodology described in Chapter 6, decision trees were constructed for each performance criteria against each of the above possibilities for growth. Figure 7.10 shows a typical average travel time performance decision tree for the different combinations of technology and configuration, assuming a 50% chance for growth. The overall expected (average) values are calculated using decision analysis for each performance criteria over the different growth possibilities. The best decision is the one that offers the best average value. These results are tabulated in Table 7.2 in the form of the best decision under uncertainty for the different performance measures.

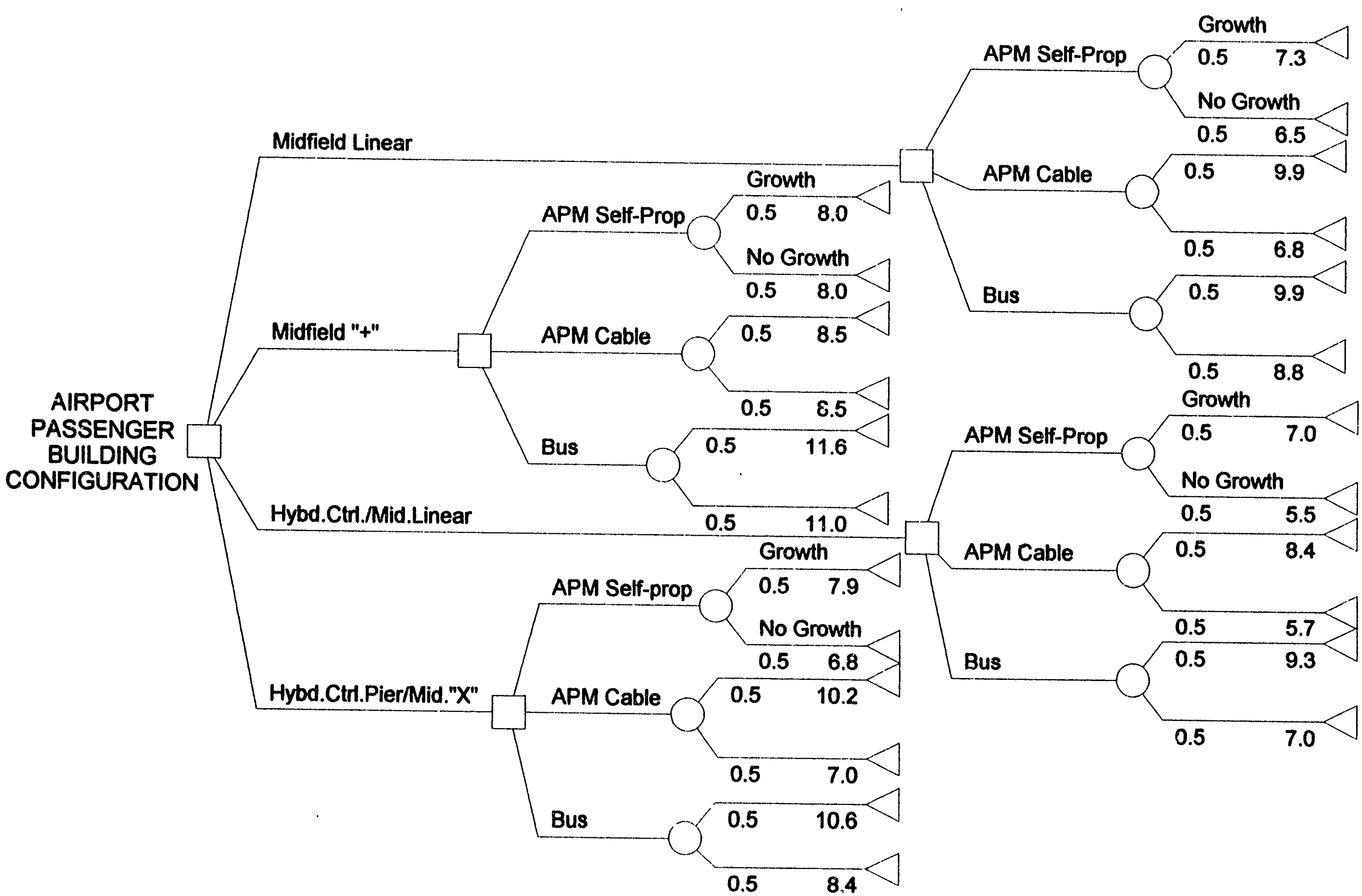


Figure 7.10 : Decision Tree for Average Travel Time (min) Performance for 50% Growth Chance

Table 7.2 : Best combination of people mover transport technology and passenger building configuration under uncertainty in traffic growth

Performance Criteria	Probability of Traffic Growth to a Larger Airport			Comments
	0	0.5	0.9	
Travel Time - Avg. - Max.	SP + HLL SP + HPX	SP + HLL SP + HPX	SP + HLL SP + M(+)	SP always better
Walk Distance - Avg. - Max.	SP/CB/Bus + HLL SP/CB/Bus + M(+)	SP/CB/Bus + HLL SP/CB/Bus + M(+)	SP/CB/Bus + HLL SP/CB/Bus + M(+)	No Dominant System
Queue - Avg. - Max.	MS + ML/M(+) / HLL/HPX MS + ML/M(+) / HLL/HPX	Bus + HLL Bus + HLL	Bus + HLL Bus + M(+)	Bus Dominant
System Cost	MS + ML	Bus + ML	Bus + ML	

Notation: SP = Self-Propelled APM, CB = Cable-Driven APM, MS = Moving Sidewalks; ML = Midfield Linear, M(+) = Midfield "+", HLL = Hybrid Centralized Linear with Midfield Linear, HPX = Hybrid Centralized Pier with Midfield "X"

Different combinations perform best under different growth possibilities and measures of performance. The ones that dominate and remain most robust to the different growth scenarios are the self-propelled APM or bus plus the hybrid centralized linear with midfield linear concept. As explained previously, the more expensive self-propelled APM could be selected in view of the sensitivity of passengers to speed and comfort. However, if it is certain that there will not be any expansion beyond Stage 1, then one could opt for the cheaper cable-driven APM as it performs almost as well as the self-propelled system for the same configuration.

If the airport has the potential for growth beyond Stage 1, it is prudent to invest in a system that provides for insurance against poor performance in the longer term. Recognizing the risk and the uncertainty in future traffic growth, one needs to provide for flexibility to be able to respond to changing conditions. Thus the initial investment in a flexible self-propelled system in Stage 1 for a hybrid centralized linear with midfield linear configuration, may be a wise decision despite its cost. It could initially be a simple dual-lane 2-car train shuttle in Stage 1 with the provision to be enlarged / modified slightly to a 3-car train over a pinched loop system in Stage 2. This provision would not be possible under a cable system given the current state of technology. At most, only an extension from a 2-car to a 3-car cable shuttle in Stage 2 is possible which gives poor and unacceptable performance.

7.2 **Baggage**

7.2.1 Best combination of technology and configuration for each size of airport

Applying the queuing model described in Chapter 5 to each combination of baggage transport system and terminal configuration, "performance profiles" are plotted over a range of loads for each of the performance measures i.e. average and maximum travel times for originating as well as terminating bags, for each of the two stages. The results of the three technologies i.e. telecar, DCV and tug/cart are combined for each configuration to demonstrate their comparative performance. Figures 7.11 and 7.12 show typical results for a larger airport (56-gate) Hybrid Centralized Linear with Midfield Linear configuration in terms of maximum travel time performance of the different systems for originating and terminating bags.

The results are averaged over the range of loads envisaged for each size of airport as identified in Table 4.5 to represent the performance of each system. For example, in the case of a larger airport, we take the average over the range of 150 to 200 bags/min for terminating bags and 100 to 150 for originating bags. The final results are tabulated in Table 7.3 for all possible combinations of technology and passenger building configuration.

For both airport sizes, the delivery times of originating bags are lower than those of terminating bags. This is to be expected as we are only considering the performance of the last bag. Unlike originating bags, the calculation of the delivery time for the last terminating bag must also take into account the processing i.e. unloading of all the other bags belonging to the same flight, thereby increasing its travel time.

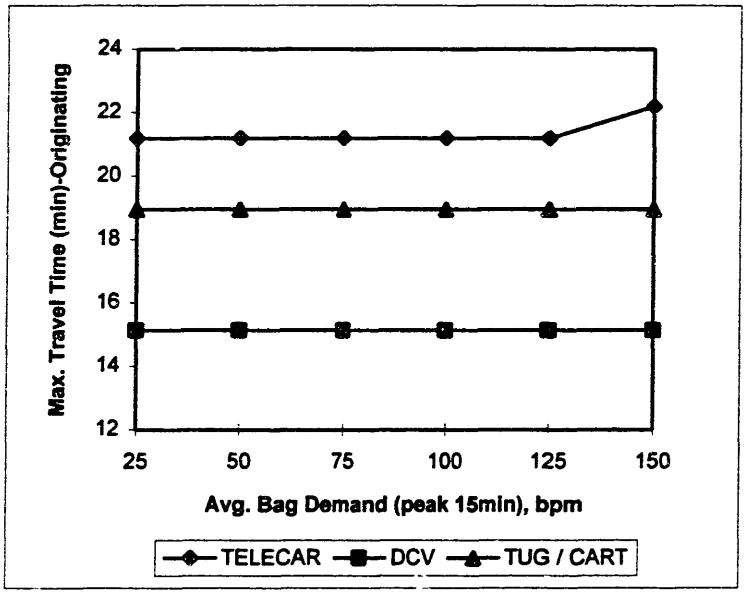


Figure 7.11 : Larger Airport - Hybrid Centralized Linear with Midfield Linear concept
Maximum Travel Time Comparison between Systems for Originating Bags

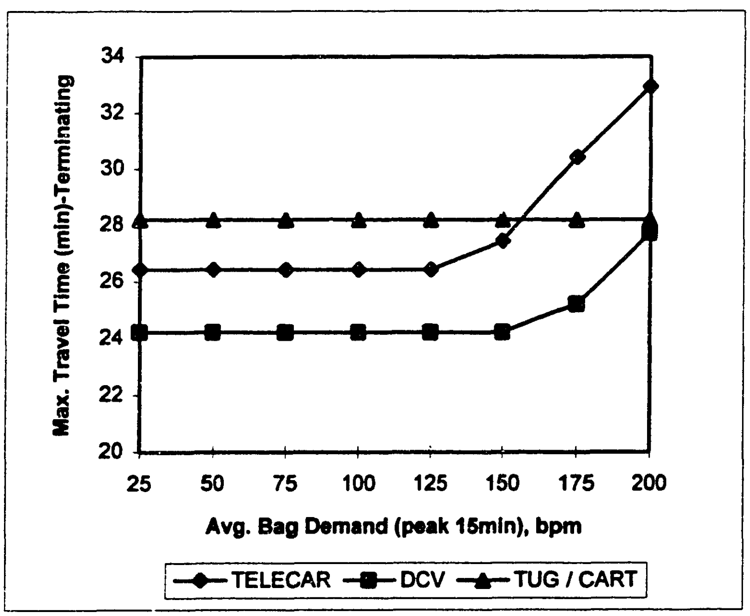


Figure 7.12 : Larger Airport - Hybrid Centralized Linear with Midfield Linear concept
Maximum Travel Time Comparison between Systems for Terminating Bags

TABLE 7.3 : Performance of Baggage Transport Technologies for various Passenger Building Configurations

Smaller Airport : 28 gates - 15 to 20 million pax/yr
Peak 15 min demand volume for Originating bags = 50 to 75 bags / min
Peak 15 min demand volume for Terminating bags = 75 to 100 bags/min

Performance criteria	Midfield Linear			Midfield "+"			Hybrid Ctrl./ Mid.Linear			Hybrid Ctrl.Pier/Mid."X"		
	Telecar	DCV	T/C	Telecar	DCV	T/C	Telecar	DCV	T/C	Telecar	DCV	T/C
T.T. for Org.bags (min) - Avg	18.0	13.1	13.9	19.3	14.5	17.6	14.2	12.6	12.9	15.9	13.2	14.1
- Max	20.6	14.1	16.2	20.5	15.2	18.2	17.1	14.0	15.1	18.5	14.1	15.3
T.T. for Ter. bags (min) - Av	25.1	21.9	23.1	26.7	23.6	26.9	21.6	20.8	22.2	22.5	21.6	23.4
- Max	29.1	24.9	25.5	28.9	25.8	27.5	24.0	22.3	24.4	23.7	22.7	24.5
System Cost per bag ($)	1.0	1.9	0.5	3.1	3.6	1.0	1.3	1.7	0.5	1.7	2.2	0.5

Larger Airport : 56 gates - 30 to 40 million pax/yr
Peak 15 min demand volume for Originating bags = 100 to 150 bags / min
Peak 15 min demand volume for Terminating bags = 150 to 200 bags/min

Performance criteria	Midfield Linear			Midfield "+"			Hybrid Ctrl./ Mid.Linear			Hybrid Ctrl.Pier/Mid."X"		
	Telecar	DCV	T/C	Telecar	DCV	T/C	Telecar	DCV	T/C	Telecar	DCV	T/C
T.T. for Org.bags (min) - Avg	17.9	13.6	15.0	19.0	14.5	17.6	16.7	13.4	14.8	17.6	14.0	16.2
- Max	21.3	15.0	18.5	20.3	15.2	18.2	21.5	15.1	19.0	20.6	15.5	19.0
T.T. for Ter. bags (min) - Av	25.1	22.2	24.2	26.2	23.5	26.9	23.6	21.8	24.0	24.5	22.7	25.5
- Max	30.1	25.2	27.7	29.0	25.6	27.5	30.2	25.7	28.2	29.3	25.9	28.3
System Cost per bag ($)	1.6	2.4	0.7	3.0	3.6	0.9	1.9	2.4	0.7	2.6	3.1	0.7

Notation : T/C - Tug and Cart; T.T. - Travel Time; Org.- Originating; Ter. - Terminating; Avg. - Average; Max. - Maximum; Ctrl. - Centralized; Mid. - Midfield

Smaller Airport (28-gate)

The relative performance of the different technologies is generally the same for all configurations. With respect to originating bags, the DCV system performs the best with maximum travel times generally below 15min. The tug and cart performs almost as well with maximum delivery times in the region of 15 to 16min, with the exception of the Midfield "+" concept (18min) because of the longer travel distances. Hence the tug and cart system generally still meets the performance requirement of 15min flight close-out time at major airports. On the other hand, the telecar system takes about 3 to 4 min longer due to the added handling activities involved e.g. bags have to be sorted, "double-handed" prior to delivery to aircraft. Depending on the concept, the maximum travel time of the telecar can go up to around 20min with the average ranging between 15 to 19min. This is unacceptable at major airports today.

As for terminating bags, the relative performance all three systems remain the same (as for originating bags), with the DCV still having the slight edge over the tug/cart with maximum times generally below 24min, and around 25min respectively. Figures 7.13 and 7.14 illustrate typical performance of the different systems of a small airport for the Hybrid Centralized Linear with Midfield Linear and Midfield "+" configurations respectively, over the different performance measures.

The results indicate that the DCV system works best with all configurations with the tug and cart system performing almost as well. From the cost perspective, the DCV system is also the most expensive, about 40% more than that of the telecar system which is in turn around five times more expensive than the tug and cart system. The telecar system is a poor performer, simply cost-ineffective. Figure 7.15 compares the cost of the different systems for the various passenger building configurations.

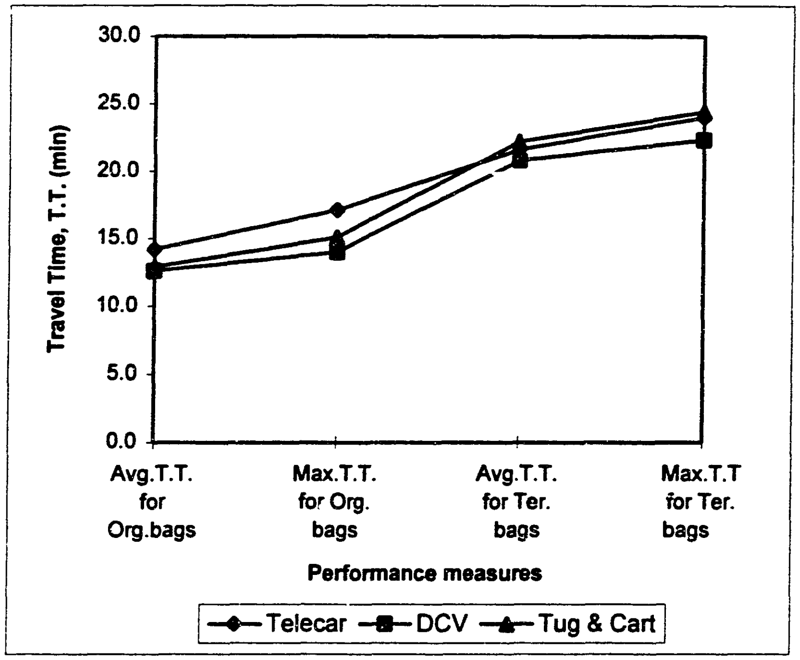


Figure 7.13 : Smaller Airport - Hybrid Centralized Linear with Midfield Linear Concept
Travel Time Comparison for Different Baggage Transport Systems

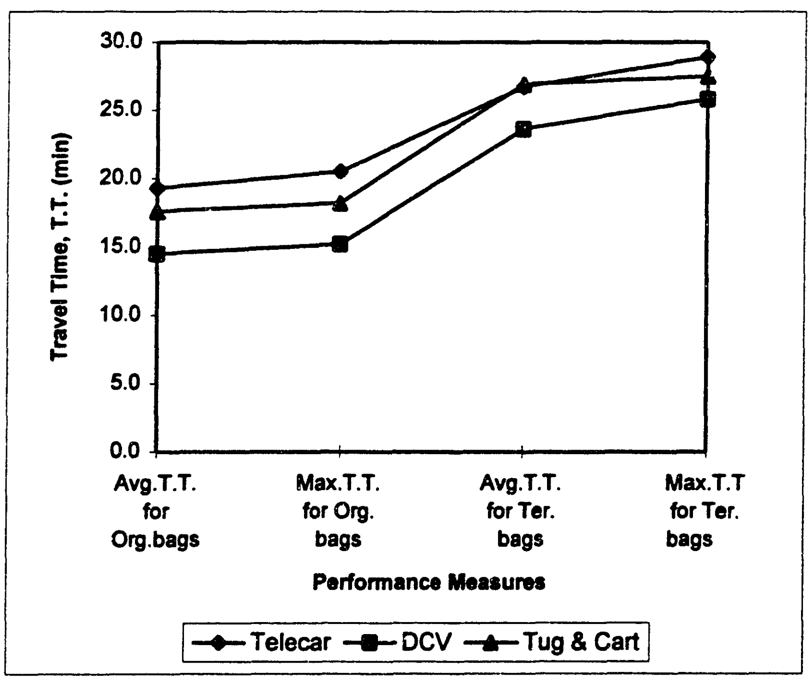


Figure 7.14 : Smaller Airport - Midfield "+" concept
Travel Time Comparison for Different Baggage Transport Systems

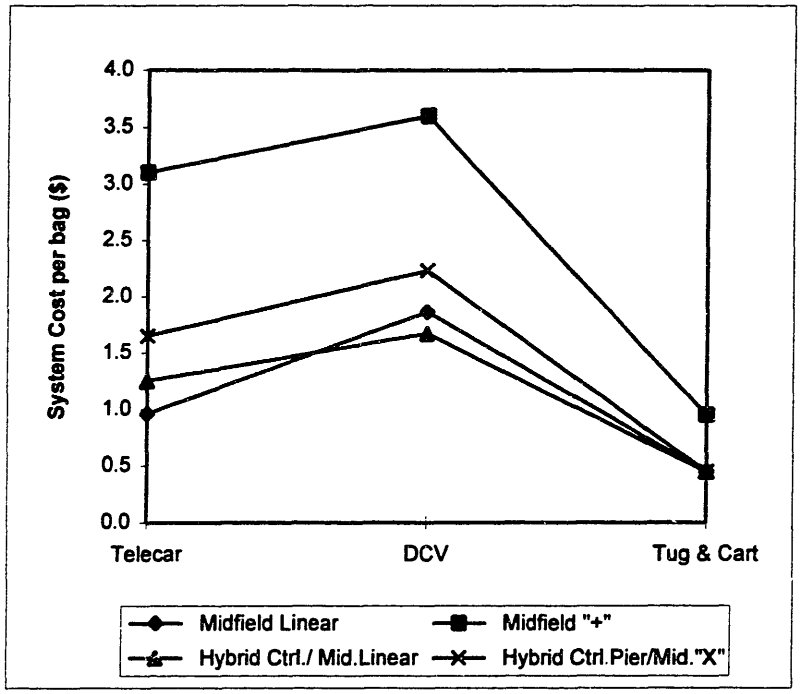


Figure 7.15 : Smaller Airport - System Cost Comparison of Baggage Transport Technologies for Different Passenger Building Configurations

Comparing the performance of the DCV over the different passenger building configurations (see Figure 7.16), it appears that it combines best with the hybrid centralized and midfield linear concept. Similar plots of the tug and cart system reveal that it performs best with the same concept (see Figure 7.17). These systems do not perform so well with the midfield "+" because of the relatively longer traveling distance (about 10% more delivery time is required). From a delivery time perspective, either the DCV or tug/cart system together with the hybrid linear concept will be able to match the high standards set. The tug and cart system is however far more economical.

Larger Airport (56-gate)

Similar to a smaller airport, the relative performances of the different systems remain alike for all configurations. However, the relative performance of the Midfield "+" configuration with respect to the other configurations in a larger airport has improved (i.e. the "gap" is narrowed) because unlike the rest where distances have increased, its distance in a larger airport remains the same as for a smaller airport (both the "+"s are symmetrically located at the same distance from the landside building). In other words, unlike its relatively poor performance initially, it now provides "competition".

For originating bags, the DCV outperforms the other systems with a maximum travel time in the region of 15min, only marginally higher than in a smaller size airport. This shows that greater benefits can be achieved with the DCV over longer distances due to its high speed performance. The tug and cart system, unlike in a small airport, does not perform as well. It can take up to 19 min with averages around 15 - 17 min. This may not be acceptable in view of the 15min standard. Unlike the DCV system, the performance of the tug and cart deteriorates over distance. The telecar system still takes a slightly longer time of up to about 21min for the same reason as in a small airport.

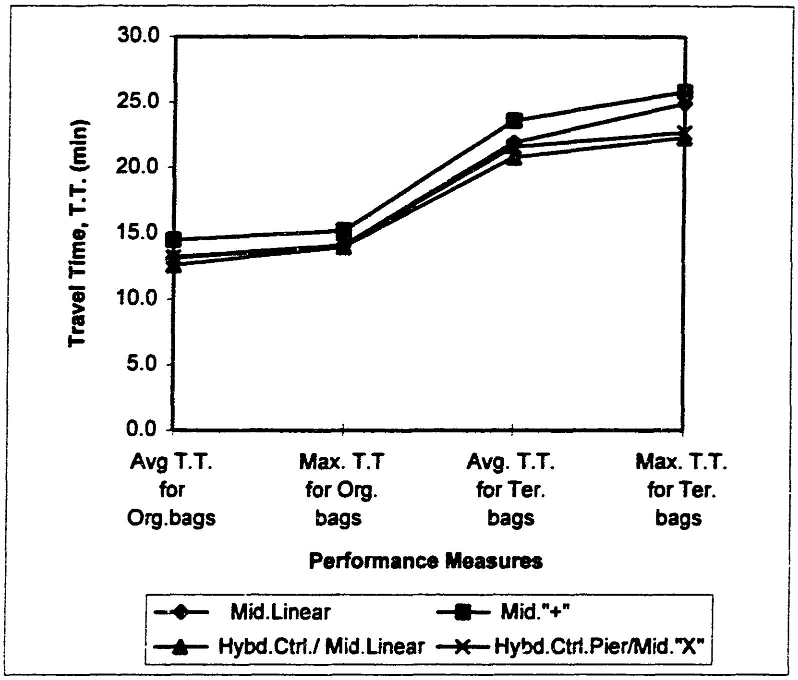


Figure 7.16 : Smaller Airport - DCV Performance Comparison for Different Passenger Building Configurations

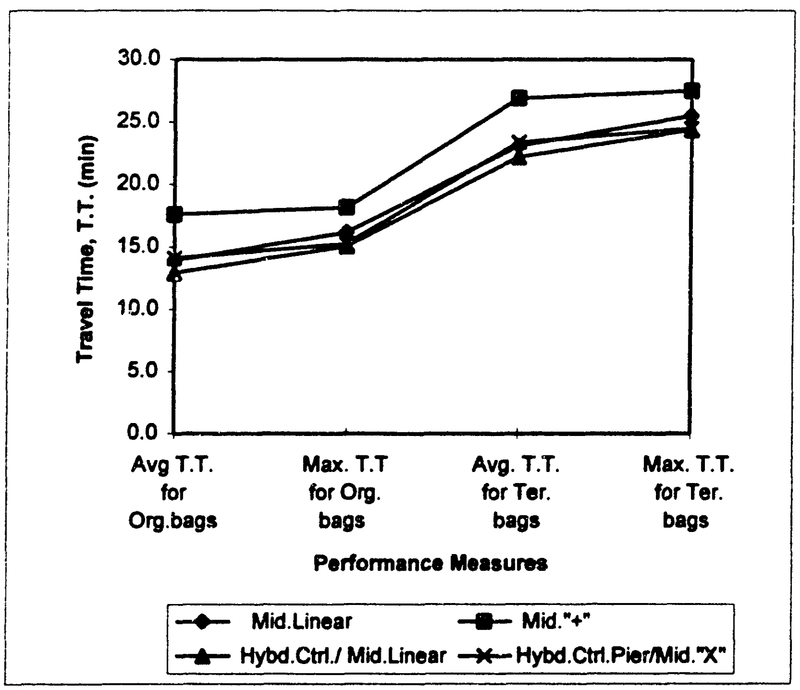


Figure 7.17 : Smaller Airport - Tug and Cart Performance Comparison for Different Passenger Building Configurations

As for terminating bags, the DCV once again comes out tops, with maximum travel times of just under 26min and an average of around 22-23min (again marginally higher than in a small airport). The tug and cart and telecar systems take up to 29min and 30min respectively. See Figure 7.18 for a typical illustration of the travel time comparison among the systems for a larger airport having a hybrid centralized linear with midfield linear configuration.

The DCV system continues to perform best for all configurations. The benefits are more significant over longer distances as demonstrated by the results for a larger airport. Unlike in a small airport, the tug and cart system does not perform as well. A comparison of Figures 7.13 and 7.18 confirms that the difference in the performance of the two systems widens with increasing distances due to airport expansion. Neither the tug and cart nor the telecar systems are able to meet the performance standards set by major larger airports.

A plot of the performance of the DCV system for the various passenger building configurations (see Figure 7.19) again confirms that it combines marginally better with the hybrid centralized linear and midfield linear configuration. This combination provides a high level of service with consistently good performance over the range of possible loads, due to its relatively shorter travel distances (some gates adjacent to the landside building) and a more balanced load distribution amongst the concourses. It is also the cheapest combination for DCV systems as illustrated in Figure 7.15. Note also that the relative performance of the midfield "+" configuration with respect to the other concepts has improved, as compared to smaller airport (i.e. the "gap" has decreased) for reasons explained earlier.

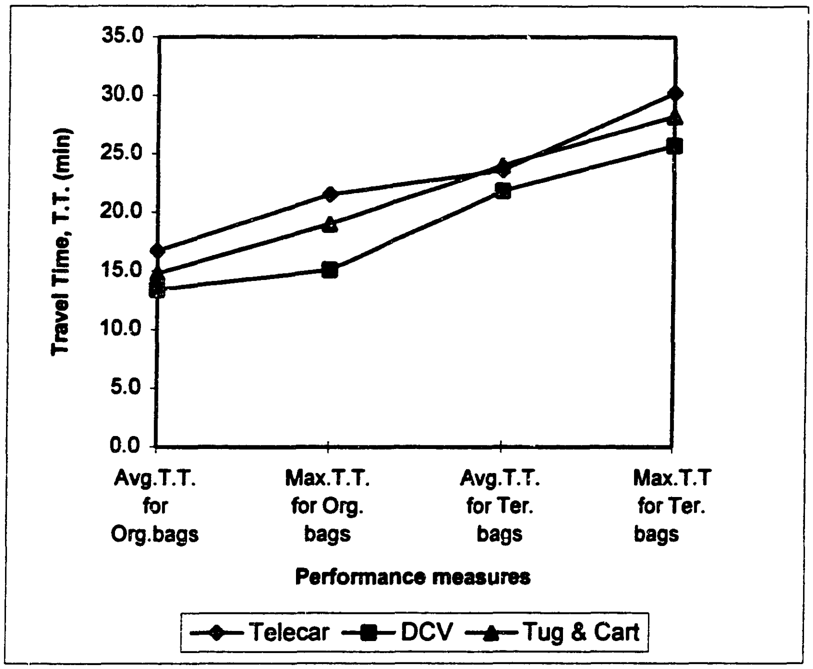


Figure 7.18 : Larger Airport - Hybrid Centralized Linear with Midfield Linear concept Travel Time Comparison for Different Baggage Transport Technologies

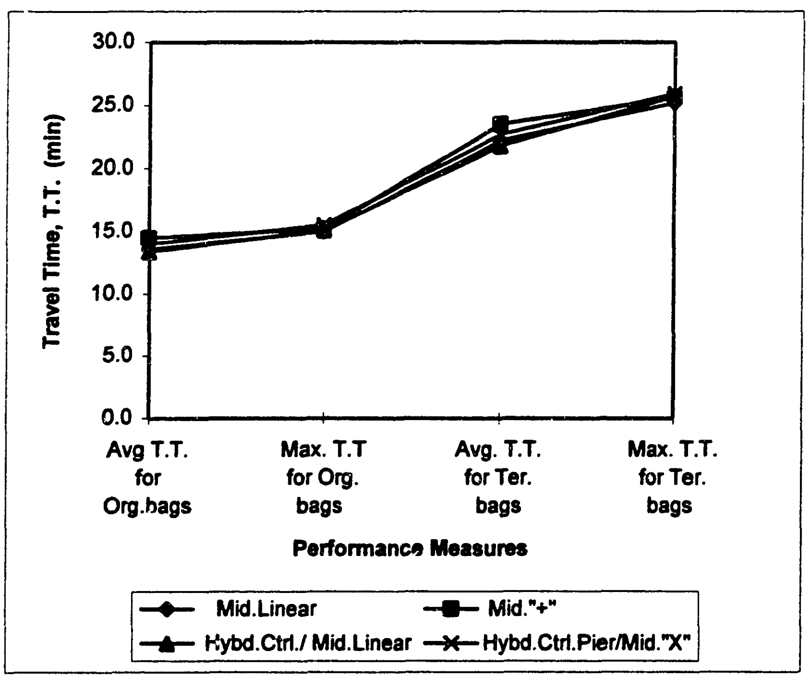


Figure 7.19 : Larger Airport - DCV Performance Comparison for Different Passenger Building Configurations

7.2.2 Best combination of technology and configuration over time

To determine the best combination over the long term, three scenarios of future traffic growth were examined :

a) No possibility for growth beyond Stage 1 (small airport) e.g. due to site constraints

b) 50% chance of possible traffic growth into Stage 2 (larger airport)

c) High 90% chance for growth i.e. high certainty that an expanded passenger building complex will be required to handle double the volume in Stage 1.

Using the methodology outlined in Chapter 6, decision trees are constructed for each performance criteria against each of the above possibilities for growth. Figure 7.20 shows a typical maximum travel time decision tree giving the range of possible alternatives for the different combinations of technology and configuration assuming a 50% chance for growth.

The overall expected (average) values are calculated using decision analysis for each performance criteria over the different growth possibilities, and the decision is the one that offers the best average value. Table 7.4 tabulates these results in the form of the best decision under uncertainty for the different performance measures.

The DCV plus Hybrid Centralized Linear with Midfield Linear configuration appears to be the best combination under practically all circumstances, except cost. However, such high investment in Stage 1 (small airport) for an expensive DCV system may not be desirable given that (as we have seen) that the tug and cart system performs almost as well in Stagc 1. Therefore it makes economic sense to opt for a tug and cart system in the first stage, but with the built-in flexibility or provision to be able to expand to a DCV system in Stage 2 as the tug and cart does not perform well over longer distances. Hence the right-of-way for a DCV system ought to be safeguarded within the tunnel during Stage 1 so that it can easily be brought into service when traffic volumes justify the expansion of the airport into Stage 2.

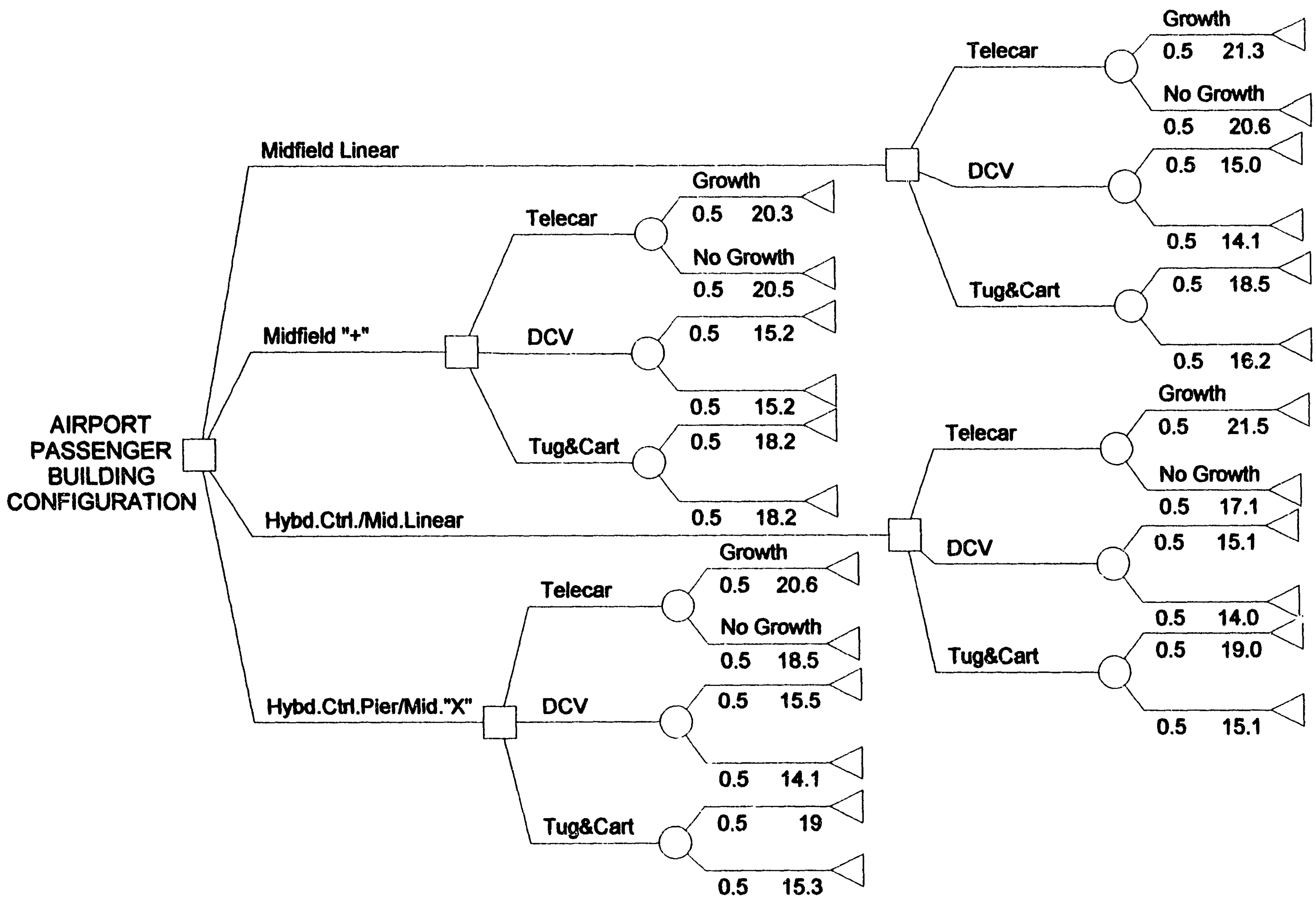


Figure 7.20 : Decision Tree for Maximum Travel Time (min) Performance (Originating) for 50% Growth Chance

Table 7.4 : Best Combination of Baggage Transport Technology and Passenger Building Configuration under Uncertainty in Traffic Growth

Performance Criteria	Probability for Traffic Growth to a Larger Airport			Comments
	0	0.5	0.9	
Originating Bags :				
Travel Time - Avg.	DCV + HLL	DCV + HLL	DCV + HLL	DCV
- Max.	DCV + HLL	DCV + HLL/ML	DCV + ML	best
Terminating Bags :				
Travel Time - Avg.	DCV + HLL	DCV + HLL	DCV + HLL	
- Max.	DCV + HLL	DCV + HLL	DCV + ML	
System Cost	T/C + HLL/ML /HPX	T/C + HLL/ML /HPX	T/C+ HLL/ML /HPX	T/C best

Notation : Avg. = Average, Max. = Maximum; DCV = Single-bag Destination Coded Vehicle, T/C = Tug and Cart, ML = Midfield Linear, HLL = Hybrid Centralized Linear with Midfield Linear, HPX = Hybrid Centralized Pier with Midfield "X"

7.3 Sensitivity of Results to Gate / Passenger Ratio

This section analyzes the impact of increasing the original gate / passenger ratio assumption of 1.6 gates/million passengers per annum to 2.8, which could be more representative of airports having a relatively larger proportion of narrow-body aircraft. Table 7.5 presents the range of loads under consideration for both small and large airports under the alternative assumption.

7.3.1 Passengers

The analysis shows that the decisions obtained under the original assumption of 1.6 gate/million passengers in Chapter 7.1 generally also holds for the alternative assumption.

With the lower loads, all technologies will experience lesser queues, reduced wait times and travel times. However, the cable-driven system which earlier encountered capacity problems for larger airports at higher loads, showed the largest improvements. The travel time on the cable system now takes about 15 to 20% longer than the self-propelled system, instead of 30 to 40% under the original assumption, while queues are about 2.5 times that of the self-propelled compared to 3 to 5 times previously. Thus the self-propelled system still outperforms the cable system and provides a superior level of service for larger airports. The cost of all systems on a per passenger basis increases under the alternative assumption because of reduced traffic.

On the whole, the results show that the relative performance of the different systems remain alike under both assumptions for both sizes of airports . Therefore it can be deduced that the best combination of technology and passenger building configuration remains robust to reasonable changes in gate/passenger ratios.

Table 7.5 : Range of loads under consideration for the two airport sizes under 2.8 gates/million passenger assumption

Traffic Type	Smaller Airport (28-gate)	Larger Airport (56-gate)
Annual Passenger Traffic	10 million	20 million
In peak 15 min period :		
Ter. pax. load (pax/min)	35	75
Ter. bag load (bag/min)	50	100
Org. bag load (bag/min)	35	75
Terminating flights	3	6

Notation : Ter. = Terminating; Org. = Originating; pax = passenger

7.3.2 Baggage

Under the alternative assumption that implies lower loads (and thus lesser delays), slight improvements in travel times of up to 15% are achieved for both the automated systems i.e. telecar and DCV. Conversely, the cost of the systems per bag are more expensive. On the whole, however, the relative performance of the different systems remain generally alike for both assumptions. Therefore, similar to the analysis for passengers, the optimal combination of bag system and configuration also remains robust to reasonable changes in gate/passenger ratios.

CHAPTER 8 - CONCLUSIONS and APPLICATIONS

Good design practice dictates that systems performance be assessed using multiple criteria over a range of possible conditions. Planners should thus view the selection of technology and configuration in terms of robust performance over the long term and multiple criteria. The inability to predict future conditions makes the selection of a robust combination critical to the long term success of an airport.

This thesis develops a methodology and a computer-based tool for establishing the multi-criteria performance of any combination of passenger/baggage transport technology and terminal configuration over a range of situations, with the aim of selecting the best "match" over the longer term.

The study focuses on Originating and Terminating traffic, as the People Mover and Baggage technologies center on providing transport between the landside building and the midfield concourses.

This thesis analyzes four possible future midfield and hybrid airport passenger building configurations together with their transport technologies. The buildings are characterized geometrically to establish an objective platform for comparison. From these geometric representations, critical inputs (e.g. distances between concourses, walk distances) for our model are determined for estimating the potential performance of any combination of technology and configuration.

8.1 Evaluation of Airport Passenger Building Configurations

From our analysis, the Hybrid Centralized Linear and Midfield Linear (HLL) configuration appears best (see Table 8.1). Given that large aircraft are usually assigned to gates closest to the center plus the fact that some of the gates are connected directly to the landside passenger building, the HLL concept provides the lowest average walk distance. It also requires the least area for passenger building and aircraft parking in view of the highly efficient use of land. Other advantages include superior aircraft maneuverability, ability to provide better level of service to different passenger types, and flexibility for future expansion and to respond to changing traffic conditions. The Midfield Linear (ML) concept fares almost as well as the HLL concept except for slightly longer average walk distances, and because it is a "pure" design, it can only provide high level of service to transfer passengers at the expense of other passenger types.

The inherent difficulty associated with the "X or +" geometry is that larger aircraft can usually be parked only at the ends of the piers and that space is "wasted" within the cul-de-sacs. The Hybrid Centralized with Midfield "X" (HPX) configuration thus has an average walk distance higher than those of the linear configurations. The maximum walk distance is shorter however. The area required for aircraft parking and passenger buildings is also more than the linear concepts, although on the aggregate, the total land area between the Runways is marginally less than the linears (due to the reduced dual apron taxiway systems required between the more closely spaced Runways). Nevertheless, the overall cost of the total land area may potentially be more than the linear concepts because more "concrete" area is required for parking of aircraft and passenger buildings. The HPX configuration also suffers from reduced aircraft maneuverability and thus a higher potential for congestion delays, especially within the cul-de-sacs. There is also lesser flexibility for expansion as compared to the linear configurations.

Table 8.1 : Rankings of Four Airport Passenger Building Configurations

Position	Configuration	Advantages	Disadvantages
1	Hybrid Centralized Linear with Midfield Linear	Lower average walk distance; efficient use of land; good aircraft maneuverability; high LOS for different passenger types; Flexibility for expansion	
2	Midfield Linear	Same as above	"Pure" design - high LOS for transfer passengers only
3	Hybrid Centralized Pier with Midfield "X"	Lower maximum walk distance; high LOS for different passenger types	"Wasted" space in cul-de-sacs - inefficient use of land; higher average walk distance; reduced aircraft maneuverability; higher potential for congestion; less flexibility for expansion
4	Midfield "+"	Lower Maximum walk distance	Same as above; Extravavant use of land - most costly; high LOS for transfer passengers only

The Midfield "+" (M+) configuration, although providing low maximum walk distance, has high average walk distance for the same reasons explained above for the HPX concept. It also requires "extravagant" use of land thus making it the most costly and unattractive configuration. Like the HPX concept, it suffers from aircraft maneuverability problems. Moreover, being a "pure" design, it serves transfer passengers well at the expense of other passenger types.

8.2 Evaluation of People Mover Technologies

The self-propelled, automated people mover system performs best both in a shuttle mode over short distances and in a pinched-loop configuration over longer distances. It possesses the flexibility for expansion and will continue to perform well at high capacities over long distances (see Table 8.2).

Cable-driven automated people mover systems are cheaper and easier to operate and perform almost as well as the self-propelled technology in the shuttle mode over short distances, but have flexibility disadvantages. Their application is limited to shuttle services and generally not suitable for distances of more than around 1.2km long, requiring multiple stops and high capacities. They suffer from capacity reduction over increasing distances, leading to a poor level of service. In short, the cable system will not maintain good performance under expansion.

Passengers generally dislike buses because they usually expose people to the weather, and their comfort is low when operating at capacity. However, buses have the advantage of providing high frequencies during peak periods. The slow speeds and the tendency to form barriers to cross travel movements are distinct drawbacks for moving sidewalks.

Table 8.2 : Rankings of People Mover Technologies

Position	Technology	Advantages	Disadvantages
1	Self-Propelled APM	Good over all distances; flexibility for expansion; higher capacity	More expensive
2	Cable-Driven APM	Good for short distance point-to-point service up to 1.2 km; Cheaper than Self - Propelled APM; Easier to operate	Less flexibility - limited to short distance shuttle only; not appropriate for multiple stops requiring high capacities, capacity reduction over longer distances giving low LOS i.e. poor performance under expansion
3	Shuttle Buses	More economical; High frequency, reduces queues	Passengers exposed to weather, comfort low i.e. low LOS
4	Moving Sidewalks	Cheapest	Slow travel speed; forms barriers to cross-travel movements

8.3 Evaluation of Baggage Transport System Technologies

The DCV system is the best performer in terms of delivery time both over short and long distances. It has the capability to accomplish both high speed transport as well as sortation of bags to every gate, and the ability for automated load/unload. Disadvantages include the cost and the high developmental risk associated with systems larger and more complex than those already in operation (see Table 8.3).

The tug and cart system is the most commonly used form of baggage transport in major airports today because of its lower capital cost, high capacity and reliability. It serves as a good "back-up" for the automated alternatives in the event of system failure. It performs almost as well as the more expensive DCV system over short distances of up to about 800m. The main disadvantage, however, would be the longer and unacceptable delivery times over increasing distances due to its lower speed capability. Hence if a tug and cart system is adopted initially, provision should be made for expansion to a DCV system in the future (if the possibility for growth exists) to ensure good performance in the long term.

The telecar system is a cost-ineffective system. Unlike the DCV, it is essentially a high-speed point-to-point multi-bag cart system for general transport only with no capability for sortation. It also requires a relatively high degree of manual interaction to load/offload the bags.

Table 8.3 : Rankings of Baggage Transport Technologies

Position	Technology	Advantages	Disadvantages
1	DCV	Good over short and long distances; high-speed transport and sortation capabilities; automated load/unload	High cost, high developmental risk for more complex systems
2	Tug / Cart	Good for short distances up to 800m; low cost; high capacity / reliability; Good "back-up" for automated systems	Poor performance over longer distances
3	Telecar	High speed point-to-point transport	Cost-ineffective; No capability for sortation; high degree of manual interaction needed

8.4 Best Combination of People Mover Technology and Airport Passenger Building Configuration

For each size of airport

For a smaller airport with 28 gates, the best combination of passenger transport technology and passenger building configuration would be the cable-driven APM system with the Hybrid centralized linear and midfield linear configuration. The cable-driven system performs almost as well as the more expensive self-propelled technology over such distances.

For a larger airport with 56 gates, the self-propelled pinched-loop APM system performs best with the same configuration. This is because, cable shuttle systems do not perform well over longer distances due to capacity problems.

Over the long term

The combination that is most robust over the longer term is the self-propelled APM plus the above hybrid linear concept.

If one is certain that there will be no expansion beyond Stage 1 (smaller airport), due for example to site constraints, then opting for the cheaper cable-driven APM system would be desirable as it performs almost equally well as the self-propelled. Otherwise, it is prudent to invest in a system that provides insurance against poor performance in the longer term, one that has the flexibility to respond to changing conditions. Hence the investment in a flexible simple shuttle self-propelled APM system in Stage 1 with the hybrid linear passenger building configuration, together with the provision for enlargement to a pinched-loop system in Stage 2 would appear to be the best decision.

Such a flexible provision cannot be achieved with the cable-driven system given the current state of technology.

8.5 Best Combination of Baggage Transport Technology and Airport Passenger Building Configuration

For each size of airport

For a smaller airport, the tug and cart system combines reasonably well with the Hybrid Centralized Linear and Midfield Linear configuration. This system performs as well as the DCV over shorter distances, and is much cheaper. The telecar is a poor performer. It is expensive, and requires longer delivery times due to the extra handling involved in sortation.

For a larger airport, given the longer distances, the DCV outperforms the alternatives. The combination with the hybrid linear concept provides a marginally higher level of service with consistently good performance over the range of loads, due to its relatively shorter travel distances(with some gates adjacent to landside) and a more balanced load distribution amongst the concourses. It is also the cheapest combination for DCV systems.

Over the long term

The DCV/Hybrid Linear combination is most robust over the long term. A tug and cart system may be adopted in the first stage, but with the built-in flexibility or provision to be able to expand to a DCV system in the future if there is a likelihood for growth. Hence the right-of-way ought to be safeguarded during Stage 1 so that the DCV can easily be brought into service when the traffic volumes justify the expansion of the airport passenger building.

8.6 Overall Evaluation of Transport Technology and Airport Passenger Buildings

The best and most robust combination that gives reasonable performance over a range of situations in the long term is the Hybrid Centralized Linear and Midfield Linear configuration, together with the Self-Propelled and DCV technologies for passengers and bags respectively. This combination provides the insurance against poor performance in the future, and the flexibility to respond to changing conditions. It is therefore the recommended solution for airport passenger buildings expected to expand to about 56 gates serving around 30 to 40 million passengers per annum.

8.7 General Applications to some Existing and Future airports

This section applies the above findings to some existing and proposed international airports around the world : London/Heathrow's proposed Terminal 5, the new Kuala Lumpur International Airport, and Singapore/Changi's proposed Terminal 3. In all cases, it is assumed that the passenger building configuration is given. This section attempts to find the technology that combines best with the chosen configuration.

<u>Proposed Terminal 5 at London/Heathrow</u>

Terminal 5, designed for about 30 to 40 million passengers per annum, is proposed to be ready early in the next century. As now planned, it would be a hybrid combination of a Centralized Linear and Midfield Linear configuration. This concept would be best served by a self-propelled pinched-loop automated people mover system and a DCV system for the transportation of passengers and bags between the landside building and the midfield concourses.

New Kuala Lumpur International Airport

This airport, expected to be completed by 1998, will be similar to the Midfield "+" configuration analyzed in this thesis. It will be designed in the first stage with a single "+" concourse for up to 25 million passengers per annum, with a doubling in capacity in the next stage through the addition of another midfield "+". Given that the distances from the landside building to either of the "+"s is around one kilometer, independent cable-driven dual-lane shuttle systems to the concourses would perform reasonably well. It will not only perform as well as the self-propelled shuttle system but will be more economical given the simplicity of the cable technology.

The DCV system would perform best for the baggage transport. Given the distances involved, the tug and cart will not be able to meet the performance standards, unless the authorities are willing are accept earlier flight close-out times of more than 20min (which means a lower level of service).

Proposed Terminal 3 at Singapore/Changi

Singapore Changi Airport's proposed third terminal will be opened early next century to handle up to 20 million passengers per annum. Together with the other two existing terminals, it will form a mega-terminal complex. Therefore the challenge is to find the best possible solution to integrate the three passenger buildings efficiently so that they function as a single unit.

Given the relatively short point-to-point distances within the new Terminal 3 and its connection to the other two terminals, a series of independent cable-driven shuttle systems (either dual-lane or single-lane bypass) will perform well. They would not only perform as well as the existing AEG Westinghouse self-propelled single-lane shuttle systems (between Terminals 1 and 2) in terms of travel time, but would be more reliable given the added redundancy. Besides, the cable system will be cheaper than a similar self-propelled shuttle system. In view of the space constraints, future expansion within the existing site is unlikely to occur.

A conventional tug and cart system from a centralized bagroom within Terminal 3 would perform reasonably well on the whole. This system would have some difficulties meeting the performance standards at a few gates at the extreme end of the proposed South pier and in particular at the proposed remote hard stands across the taxiway bridge. Hence it is prudent to provide during the construction of Terminal 3 for a right-of-way (including space for a decentralized baggage processing zone in the extreme pier) for a possible DCV operation in the future to serve these far gates if problems develop in meeting the service standards.

This thesis demonstrates that the use of the telecar system is cost-ineffective. This technology is not only expensive, but often requires longer delivery times than the tug and cart system because of the extra "handlings" involved, as observed at Singapore/ Changi. It is recommended that the existing inter-terminal telecar system (for interline transfer bags) not be expanded/extended from Terminal 2 (as proposed) to serve the new Terminal 3. The tug and cart should continue to be used instead, but through a new tunnel that will have to be constructed between Terminals 2 and 3 to reduce the travel distances.

APPENDIX A : Existing Automated Airport People Mover Systems

Continent	Country	Airports	Operational Configuration	Connection	System	Year
ASIA	JAPAN	OSAKA - KANSAI	Dual lane shuttle	Intra-Terminal	self-prop	1995
ASIA	JAPAN	TOKYO NARITA - T2	Single lane bypass shuttle	Terminal to Gate	cable	1992
ASIA	S'PORE	CHANGI (T1 - T2)	Single lane shuttle	Inter-Terminal	self-prop	1990
ASIA	S'PORE	CHANGI - Airside	Single lane shuttle	Inter-Terminal	self-prop	
ASIA	S'PORE	CHANGI - Landside	Single lane shuttle	Inter-Terminal	self-prop	
EUROPE	FRANCE	PARIS - ORLY		Landside		1991
EUROPE	GERMANY	FRANKFURT MAIN	Pinch Loop	Inter-Terminal	self-prop	1994
EUROPE	UNITED KINGDOM	BIRMINGHAM	Single lane shuttle	Landside	maglev	1984
EUROPE	UNITED KINGDOM	LON-GATWICK,Syst 1	Dual lane shuttle	Terminal to Gate	self-prop	1983
EUROPE	UNITED KINGDOM	LON-GATWICK,Syst 2	Dual lane shuttle	Inter-Terminal	self-prop	1988
EUROPE	UNITED KINGDOM	LON-STANSTED	Pinch Loop	Terminal to Gate	self-prop	1991
NORTH AMERICA	UNITED STATES	ATLANTA	Pinch Loop	Terminal to Gate	self-prop	1980
NORTH AMERICA	UNITED STATES	CHICAGO O'HARE	Pinch Loop	Landside	self-prop	1993
NORTH AMERICA	UNITED STATES	CINCINNATI	Dual lane shuttle	Intra-Terminal	cable	1994
NORTH AMERICA	UNITED STATES	DENVER	Pinch Loop	Terminal to Gate	self-prop	1993

Continent	Country	Airports	Operational Configuration	Connection	System	Year
NORTH AMERICA	UNITED STATES	DFW - AIRTRANS	Loop	Landside	self-prop	1974
NORTH AMERICA	UNITED STATES	DFW - TrAAm	Loop	Intra-Terminal	self-prop	1991
NORTH AMERICA	UNITED STATES	HONOLULU	Pinch Loop	Landside	self-prop	1996
NORTH AMERICA	UNITED STATES	HOUSTON	Loop	Landside	self-prop	1972
NORTH AMERICA	UNITED STATES	LAS VEGAS	Dual lane shuttle	Terminal to Gate	self-prop	1985
NORTH AMERICA	UNITED STATES	MIAMI	Dual lane shuttle	Terminal to Gate	self-prop	1980
NORTH AMERICA	UNITED STATES	NEWARK	Pinch Loop	Landside	self-prop	1995
NORTH AMERICA	UNITED STATES	ORLANDO	Dual lane shuttle	Terminal to Gate	self-prop	1981
NORTH AMERICA	UNITED STATES	PITTSBURGH	Dual lane shuttle	Terminal to Gate	self-prop	1992
NORTH AMERICA	UNITED STATES	SEATTLE	Loop	Terminal to Gate	self-prop	1973
NORTH AMERICA	UNITED STATES	TAMPA - AIRSIDE	Dual lane shuttle	Terminal to Gate	self-prop	1971
NORTH AMERICA	UNITED STATES	TAMPA - LANDSIDE	Pinch Loop	Terminal to Garage	self-prop	1991

APPENDIX B : Cost of Existing Automated Airport People Mover Systems

Continent	Airports	Length(lane-km)	Peak Hour Cap.	Syst Cost/km/pk pax($)	OM Cost/Ann pax($)	Year of OM cost
ASIA	CHANGI (T1 - T2)			2600	0.18	1993
ASIA	CHANGI - Airside	0.57	1800			
ASIA	CHANGI - Landside	0.67	3200			
ASIA	OSAKA - KANSAI	3.2				
ASIA	TOKYO NARITA - T2	0.56	9400	4500		
EUROPE	BIRMINGHAM	1.25			0.14	1987
EUROPE	FRANKFURT MAIN	3.4	4400	5945		
EUROPE	LON-GATWICK,Syst 1	0.6	4000		0.06	1990
EUROPE	LON-GATWICK,Syst 2	2.4	3780		0.25	1990
EUROPE	LON-STANSTED	2.6	2200	5120		
EUROPE	PARIS - ORLY	14			5	1992
NORTH AMERICA	ATLANTA	3.8	9000		0.17	1992
NORTH AMERICA	CHICAGO O'HARE	8.8	2400	6460		

Continent	Airports	Length(lane-km)	Peak Hour Cap.	Syst Cost/km/pk pax($)	OM Cost/Ann pax($)	Year of OM cost
NORTH AMERICA	CINCINNATI	0.74	5600	4040		
NORTH AMERICA	DENVER	3.9	6000	3590		
NORTH AMERICA	DFW - AIRTRANS	20.9			0.6	1987
NORTH AMERICA	DFW - TrAAm	1.5				
NORTH AMERICA	HONOLULU	4.1	8300	2560		
NORTH AMERICA	HOUSTON	2.3			0.4	1988
NORTH AMERICA	LAS VEGAS	0.8	10000		0.18	1988
NORTH AMERICA	MIAMI	0.8	9000		0.14	1982
NORTH AMERICA	NEWARK	6.4	2600	7360		
NORTH AMERICA	ORLANDO	3.5	36000		0.08	1980
NORTH AMERICA	PITTSBURGH	1.5	6600	1685		
NORTH AMERICA	SEATTLE	2.8	21600		0.07	1980
NORTH AMERICA	TAMPA - AIRSIDE	3.3	25300		0.05	1982
NORTH AMERICA	TAMPA - LANDSIDE	1.1			0.09	1993

APPENDIX C : Some Existing Centralized Bag Systems

Continent	Country	Airports	Terminals	Bagroom	Sortation	Transport System	Year
ASIA	HONG KONG	KAI TAK		Centralized	Auto Pusher	Tug and Cart	
ASIA	JAPAN	OSAKA- KANSAI		Centralized	Auto Tilt-Tray/Manual	Tug and Cart	1994
ASIA	SINGAPORE	CHANGI	T1	Centralized	Manual	Tug and Cart	1993
ASIA	SINGAPORE	CHANGI	T2	Centralized	Auto Tilt-Tray	Tug and Cart	1990
AUSTRALIA	AUSTRALIA	SYDNEY		Centralized	Auto Pusher	Tug and Cart	1992
EUROPE	BELGIUM	BRUSSELS		Centralized	Auto Tilt-Tray	Tug and Cart	1993
EUROPE	FRANCE	PARIS - CDG	T2 C and M	Centralized	Auto Tilt-Tray	Tug and Cart	1993
EUROPE	NETHERLANDS	AMS-SCHIPHOL	T Central	Centralized	Auto Tilt-Tray	Tug and Cart	
EUROPE	NETHERLANDS	AMS-SCHIPHOL	T West	Centralized	Auto Vertisorter/Manual	Tug and Cart	1993
EUROPE	UNITED KINGDOM	LON-HEATHROW	T3	Centralized	Auto Pusher	Tug and Cart	1990
EUROPE	UNITED KINGDOM	LON-HEATHROW	T4	Centralized	Auto Tilt-Tray	Tug and Cart	1992
EUROPE	UNITED KINGDOM	MANCHESTER	T2	Centralized	Auto Tilt-Tray	Tug and Cart	1993
NORTH AMERICA	UNITED STATES	ATLANTA	DELTA	Centralized	Auto Tilt-Tray	Telecar	1981
NORTH AMERICA	UNITED STATES	BOSTON	AMERICAN	Centralized	Auto Pusher	Tug and Cart	1990
NORTH AMERICA	UNITED STATES	CHICAGO O'HARE	UNITED	Centralized	Auto Pusher	Tug and Cart	1987
NORTH AMERICA	UNITED STATES	LOS ANGELES-LAX	DELTA	Centralized	Auto Pusher	Tug and Cart	
NORTH AMERICA	UNITED STATES	NASHVILLE	AMERICAN	Centralized	Auto Pusher	Tug and Cart	
NORTH AMERICA	UNITED STATES	NEW YORK JFK	AMERICAN	Centralized	Auto Pusher	Tug and Cart	1989
NORTH AMERICA	UNITED STATES	NEW YORK JFK	LUFTHANSA - IAB	Centralized	Auto Pusher	Tug and Cart	
NORTH AMERICA	UNITED STATES	NEW YORK JFK	TWA	Centralized	Auto Pusher	Tug and Cart	1981

APPENDIX D : Some Existing Decentralized Bag Systems

Continent	Country	Airports	Terminals	Bagroom	Sortation	Transport System	Year
EUROPE	GERMANY	MUNICH	T A,B,C,D,Z	Decentralized	Auto Tilt-Tray	Tug and Cart	1992
NORTH AMERICA	UNITED STATES	CINCINNATI	DELTA	Decentralized	Auto Tilt-Tray		1994
NORTH AMERICA	UNITED STATES	DENVER	UNITED	Decentralized	SBDCV	SBDCV	1995
NORTH AMERICA	UNITED STATES	NEWARK NJ	CONTINENTAL	Decentralized	Auto Pusher	Conveyor	1987
NORTH AMERICA	UNITED STATES	PITTSBURGH	USAir	Decentralized	Auto Pusher / Manual	High Speed Conveyor	1992

APPENDIX E : Cost of Some Existing Baggage Handling Systems

Continent	Airports	Terminals	Pk Hr (Or+Xfer) Cap	System Cost / pk bag ($1993)
ASIA	CHANGI	T1	4860	814
ASIA	CHANGI	T1 / T2	2400	2530
ASIA	CHANGI	T2	6600	1630
ASIA	KAI TAK		3200	3590
ASIA	OSAKA- KANSAI		7000	
AUSTRALIA	SYDNEY		6000	4020
EUROPE	AMS-SCHIPHOL	T Central	8000	DEM 5250
EUROPE	AMS-SCHIPHOL	T West	8700	2052
EUROPE	BRUSSELS		9600	3125
EUROPE	LON-HEATHROW	T3	36000	
EUROPE	LON-HEATHROW	T4	14000	
EUROPE	MANCHESTER	T2	2700	4433
EUROPE	MUNICH	T A,B,C,D,Z	19200	3008
EUROPE	PARIS - CDG	T2 C and M	12960	4456
NORTH AMERICA	ATLANTA	DELTA	24000	
NORTH AMERICA	BOSTON	AMERICAN	3000	425

Continent	Airports	Terminals	Pk Hr (Or+Xfer) Cap	System Cost / pk bag ($1993)
NORTH AMERICA	CHICAGO O'HARE	UNITED	26400	2000
NORTH AMERICA	CINCINNATI	DELTA	18000	1580
NORTH AMERICA	DENVER	UNITED	40000	4800
NORTH AMERICA	LOS ANGELES-LAX	DELTA	6600	
NORTH AMERICA	NASHVILLE	AMERICAN	3900	
NORTH AMERICA	NEW YORK JFK	AMERICAN	3000	2630
NORTH AMERICA	NEW YORK JFK	LUFTHANSA - IAB	600	
NORTH AMERICA	NEW YORK JFK	TWA	6000	2390
NORTH AMERICA	NEWARK NJ	CONTINENTAL	5250	4850
NORTH AMERICA	PITTSBURGH	USAir	21600	1554

APPENDIX F : Comparison of System Characteristics for Different Combinations of People Mover Technologies and Passenger Building Configurations

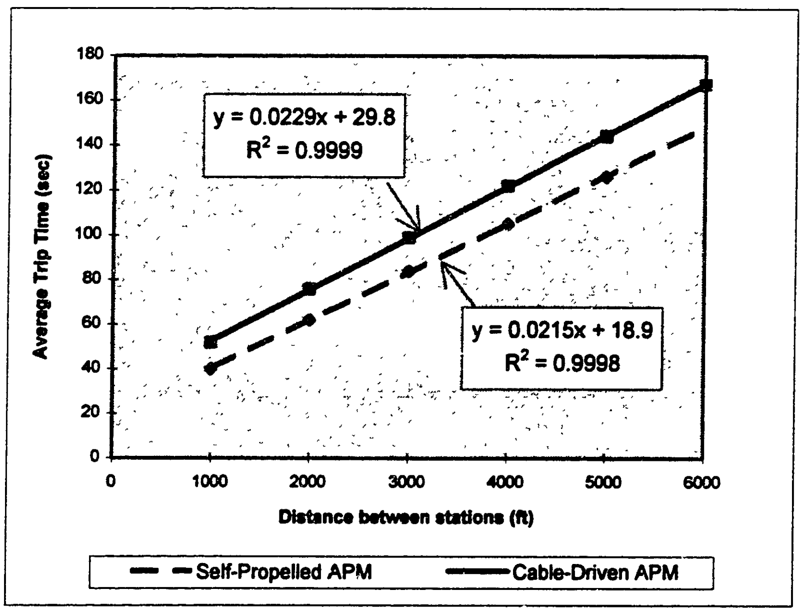
Description	Midfield Linear		Midfield "+"		Hybd.Ctrl./Mid.Linear		Hybd.Ctrl.Pier/Mid."X"	
APM Self-Propelled	Small A/P	Large A/P	Small A/P	Large A/P	Small A/P	Large A/P	Small A/P	Large A/P
a) System Type	2-v Shuttle	3-v Pinch	2-v Shuttle	2-v Shuttle*2	2-v Shuttle	3-v Pinch	2-v Shuttle	3-v Pinch
b) Headway (sec)	68	90	118	118	74	90	85	90
c) Capacity (ppmpd)	177	200	101	101*2 = 202	161	200	141	200
d) Transit Time (sec)								
2nd concourse to landside	N/A	119	N/A	93	N/A	125	N/A	148
1st concourse to landside	43	43	93	93	49	49	60	60
APM Cable-Driven	Small A/P	Large A/P	Small A/P	Large A/P	Small A/P	Large A/P	Small A/P	Large A/P
a) System Type	2-v shuttle	3-v shuttle	2-v shuttle	2-v shuttle*2	2-v shuttle	3-v shuttle	2-v shuttle	3-v shuttle
b) Headway (sec)	80	169	134	134	87	176	99	201
c) Capacity (ppmpd)	149	106	89	89*2 = 178	137	102	121	90
d) Transit Time (sec)								
2nd concourse to landside	N/A	144	N/A	109	N/A	151	N/A	176
1st concourse to landside	55	55	109	109	62	62	74	74
BUS	Small A/P	Large A/P	Small A/P	Large A/P	Small A/P	Large A/P	Small A/P	Large A/P
a) No. of Vehicles								
1st concourse	12	7	12	12	12	7	12	8
2nd concourse	N/A	10	N/A	12	N/A	11	N/A	13
b) Headway (sec)								
1st concourse	35	60	57	57	38	65	43	64
2nd concourse	N/A	59	N/A	57	N/A	56	N/A	57
c) Travel Time (min)								
1st concourse	1	1	3.2	3.2	1.3	1.3	1.8	1.8
2nd concourse	N/A	2.4	N/A	3.2	N/A	2.7	N/A	3.6
d) Capacity (ppmpd)								
1st concourse	170	99	106	106	158	92	141	94
2nd concourse	N/A	102	N/A	106	N/A	106	N/A	106

NOTE : Assume APM station dwell = 25 sec; APM vehicle capacity = 100 pax; Moving Sidewalk Capacity = 160 ppmpd

APPENDIX G : Automated People Mover System Trip Time Data

Average On-System Trip Time (sec) for shuttle systems

Distance (ft)	Self-Propelled [AEG 1995]	Cable-Driven [OTIS 1995]
1000	40	52
2000	62	76
3000	84	99
4000	105	122
5000	126	144
6000		167



APPENDIX H - Sample Calculations of a self-propelled pinched-loop APM system for a hybrid centralized linear with midfield linear 56 gate (stage 2) configuration.

Given the following data :

a) Passengers arrive at the rate of 200 passengers per min (ppmpd) during the peak 15 min surge period

b) Three-car train of 100 pax/car

c) Constant headway of 90 seconds (includes station dwell time of assumed 25 sec)

d) Service capacity = 3600/90*100*3 = 12000 pphpd or 200 ppmpd

e) Load distributed to the centralized linear and two midfield concourses in the proportion 0.18 : 0.32 : 0.50. This is based on total aircraft seat capacity at the respective concourse.

Analysis of the second midfield concourse (avg. and max. walk dist. = 350m and 585m respectively, total transit station-to-station distance = 888m; see Figure H.1):

1. Demand rate = 0.5*200 = 100 ppmpd

   Service rate = 200ppmpd

2. Since demand < service and no queues previously, actual service rate = 100 ppmpd

3. Using discrete time intervals of 0.5min, at **time t = 1 min** :

   Cumulative pax demand = 100 ppmpd * 1 = 100 pax

   Cumulative pax served = 100 ppmpd * 1 = 100 pax

   Actual / observed cumulative pax served = 0, since t = 1 < headway of 1.5min assuming 1st arriving pax just misses the train)

4. Queue (1) = 100 - 0 = 100 pax

   Cumulative wait time,CWT (1) = (100 - 0)*(1 - 0.5) + CWT (0.5) = (100*0.5) + 25

   = 75 pax-min

   Wait time of 100th pax who arrives at t = 1 is = 1.5min(headway) - 1min = 0.5min

5. Spreadsheet calculates for the entire time period under consideration. The following is the output :

Cumulative total wait time = 750 pax-min

Average wait time in queue = 750 / cumulative dmd. for pk 15min

= 750 / (100*15) = 0.5 min

Maximum wait time = 1.5 min i.e. one headway interval

Average queue = 750 / total time interval beginning and ending with no pax in system

= 750 / 15 = 50

Maximum queue = 100 pax < 150 at the moment just before the train arrives. This shortfall is due to the inherent rounding-off errors caused by the chosen discrete time interval of 0.5min used throughout this study. It has been decided, for practical reasons, not to reduce the discrete time interval to less than 0.5 min even though more accurate results can be achieved. Given the high level of uncertainty and the approximate nature of the fluid model, it would not be worthwhile to go for high accuracy.

6. Average door-to-door travel time = avg. walk time + avg. wait time + transit time

Avg. walk time = 350m / 60m/min(assume walk spd.) = 5.8min

Avg. wait time in queue = 0.5min

Transit time,TT (assume constant) = TT (2nd to 1st concourse) + dwell time at 1st concourse + TT (1st concourse to terminal)

= [21.5*(455*3.28/1000) + 18.9] + 25 + [21.5*(433*3.28/1000) + 18.9]

= 125 sec or 2.1 min

Average door-to-door travel time = 5.8 + 0.5 + 2.1 = 8.4 min

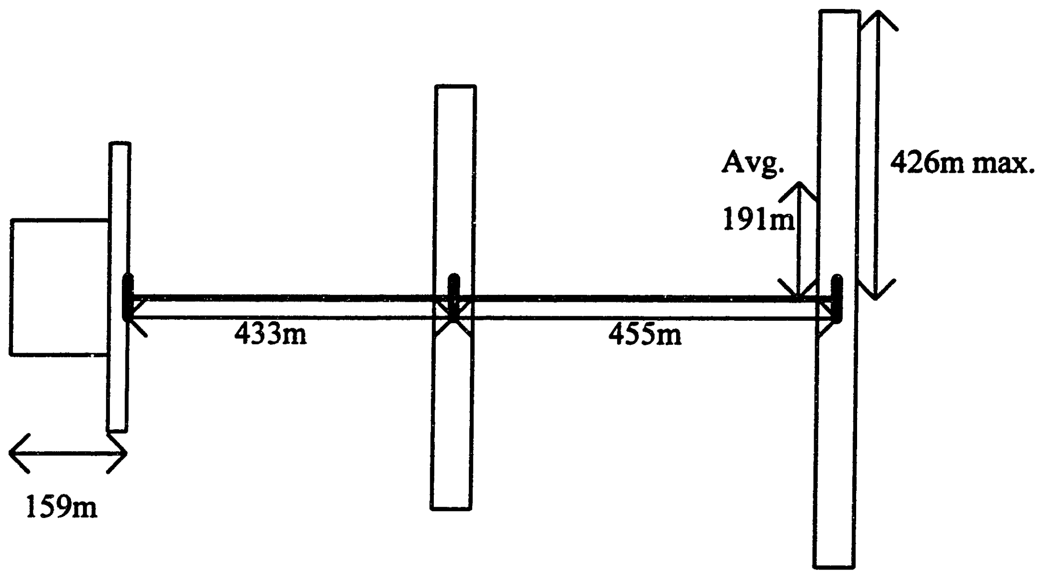
Maximum door-to-door travel time = 585/60 + 1.5 + 2.1 = 13.3 min

Transit time calculations are based on the equations presented under the assumptions in Chapter 4.

Analysis of the 1st midfield concourse follows the same methodology as the above, except that that following factors will have to be taken into consideration :

a) service capacity is reduced. The remaining service capacity available to serve this concourse is the original system capacity less the actual capacity provided to serve the previous(2nd) concourse. Hence service capacity = 200 - 100 = 100 ppmpd

b) walk distances and transit distance are different.



Walk Distance for second midfield concourse :

Average = 191 + 159 = 350m

Maximum = 426 + 159 = 585m

Total Transit Distance = 433 + 455 = 888m

Figure H.1 : Determination of Distances for Sample Calculations

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